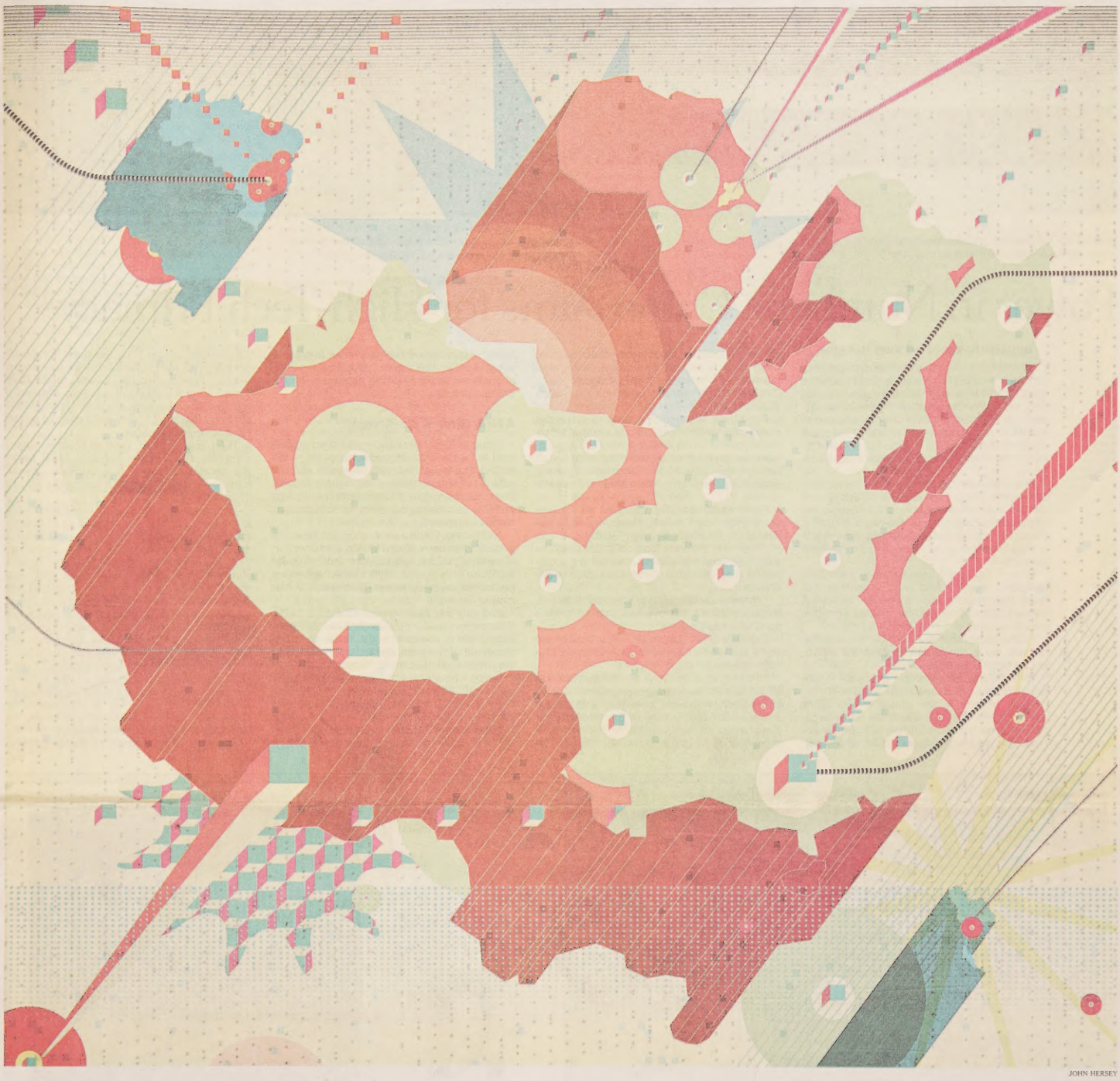
The New York Times

The Future of Computing



JOHN HERSEY

What's next? If we had a supercomputer that could predict the future, we would tell you. Then again, if the past is any guide, the predictions would certainly be wrong. This special issue takes a many-faceted look at a set of technologies that are changing the world in more ways than could ever have been foreseen. Some things are clear already: The world of innovation is undergoing tectonic shifts, and the future is likely to look less like Silicon Valley, more like China and Africa. Beyond that? As Theodor Holm Nelson points out in the essay that concludes this issue, we are definitely headed somewhere: "A wall? A cliff? A new dawn? We must choose wisely, as if we could."

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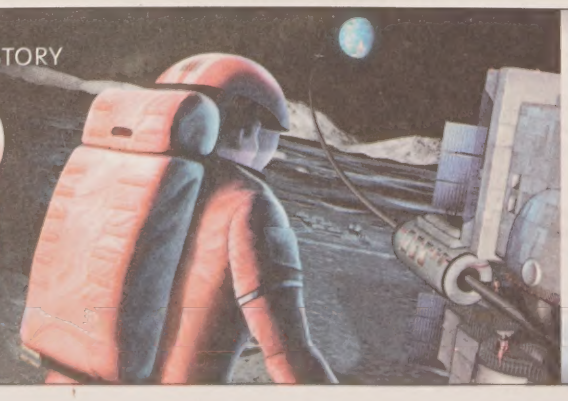

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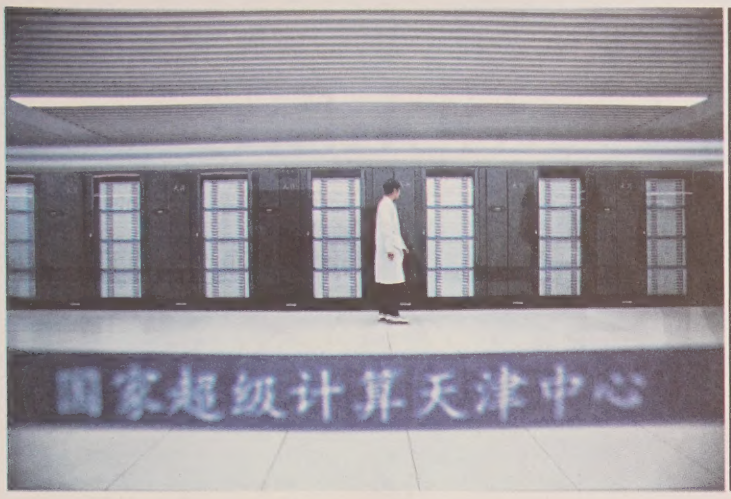
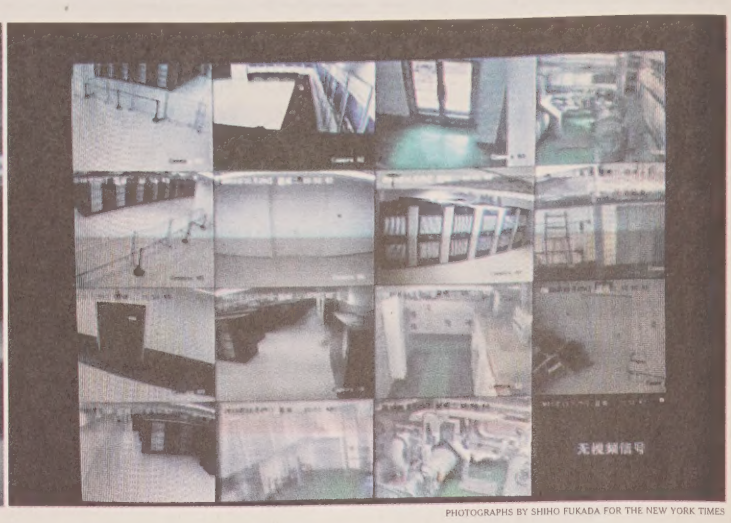


SPEED The Chinese Tianhe-1A supercomputer briefly became the world's fastest in late 2010.



PHOTOGRAPHS BY SHIHO FUKADA FOR THE NEW YORK TIMES

MIGHT A bank of monitors showing the Tianhe-1A at the National Supercomputer Center in Tianjin.

Power in Numbers: China Aims for High-Tech Primacy

By DAVID BARBOZA and JOHN MARKOFF

BEIJING — In an otherwise nondescript conference room, Wu Jianping stands before a giant wall of frosted glass. He toggles a switch and the glass becomes transparent, looking down on an imposing network operations center full of large computer displays. They show maps of China and the world, pinpointing China's IPv6 links, the next generation of the Internet.

China already has almost twice the number of Internet users as in the United States, and Dr. Wu, a computer scientist and director of the Chinese Educational and Research Network, points out that his nation is moving more quickly than any other in the world to deploy the new protocol.

IPv6 — Internet Protocol version 6 — offers advanced security and privacy options, but more important, many more I.P. addresses, whose supply on the present Internet (IPv4) is almost exhausted.

"China must move to IPv6," Dr. Wu said. "In the U.S., some people don't believe it's urgent, but we believe it's urgent."

If the future of the Internet is already in China, is the future of computing there as well?

Many experts in the United States say it could very well be. Because of the ready availability of low-cost labor, China has already become the world's dominant maker of computers and consumer electronics products. Now, these experts say, its booming economy and growing technological infrastructure may thrust it to the forefront of the next generation of computing.

For China, the quest to develop advanced computing centers is not simply a matter of national pride. It is an attempt to lay the groundwork for innovative Chinese companies and to reshape the technological landscape by doing something more than assembling the world's desktop PCs.

Never mind that there may be no Chinese Steve Jobs, said Clyde V. Prestowitz Jr., president of the Economic Strategy Institute.

"There are different kinds of innovation," he said. "We tend to equate innovation with companies that start from garages based on brainstorms.

"There is another kind of innovation that results in constant improvement that we are not good at — and they are."

The view is not universal. Still, other experts say it would be a mistake to underestimate China's capacity for rapid progress.

"When I went to China for the first time in 1978, I saw workers stringing together computer memories with sewing needles," said Patrick J. McGovern, the founder of the International Data Group, an early investor in Tencent Holdings, one of the most successful Chinese Internet companies. "Now innovation is accelerating, and in the future, patents on smartphones and tablets will be originated by the Chinese people."

A New Kind of Challenge

Going back six decades — to Eniac, considered to be the first electronic computer — the United States has set both the pace and the path of modern computing and communication. From mainframes to iPhones, from the Arpanet to WiFi, innovation has been as American as Norman Rockwell.

And for more than a generation, the hub of innovation has been Silicon Valley, a multicultural melting pot that has supported the singular amalgam of computer-hacker ethos and entrepreneurial aggressiveness that made it the envy of the world.

Probably the most serious challenge to the Valley's dominance came in the late 1980s from Japan, which seemed on the brink of taking command of the semiconductor and computer industries until its economy foundered.

Today, China poses a very different kind of challenge. While Japan's economy has long been driven by exports, China will soon have the world's largest domestic market for both Internet commerce and computing.

The world took notice of Chinese technological prowess in late 2010, when a Chinese supercomputer, the Tianhe-1A, briefly became the world's fastest. Though it was made from American processors and was soon surpassed by a Japanese machine, it was still indisputable evidence that the Chinese had achieved world-class computing designs.

Then, this October, another Chinese supercomputer, the Sunway Bluelight MPP, broke the petaflop barrier — a quadrillion calculations per second — putting it among the world's 20 fastest computers.

This machine proved even more surprising in the West. Not only was it based on a Chinese-made microprocessor, but it also achieved a significant advance in low-power operation. That might indicate the Chinese now have a significant lead in "performance per watt" — a measure of energy-efficient computing that will prove crucial to reaching the next generation of so-called exascale supercomputers, which are computers that will be a thousand times faster than the world's fastest today, and which are scheduled to arrive by the end of this decade.

"This is what Chinese companies need to do," said Hu Weiwu, a professor at the Chinese Academy of Sciences who is the chief designer of another Chinese family of microprocessor chips. "We can send a spaceship to space. We can design high-performance computers."

American officials agree, saying the Chinese

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government's investment in supercomputing is paying off.

"The overall point of all of this is that the Chinese understand the importance of high-performance computing," said Donna Crawford, the associate director of computation at the Lawrence Livermore National Laboratory. "They are executing on the plan as a key enabler for their whole society."

Obstacles to Dominance

Last year, in an interview that would have been seen as extraordinary if the remarks had been made by a United States president, Prime Minister Wen Jiabao committed China to creating an "Internet of things."

Connecting homes and smart power grids has been a driving principle behind the next-generation Internet in the United States. And it goes hand in hand with "ubiquitous computing," the idea that computing power transforms everyday devices like smartphones and digital music players.

But China's efforts at dominance are hardly without obstacles. The country has fallen far short on a decade-long commitment to build the world's leading semiconductor industry, and it still imports a vast majority of microchips for the products it assembles. Its best chip factories are two to three generations behind world leaders like Intel, in the United States, and T.S.M.C., in Taiwan.

China's great weakness may prove to be too much government control. Chinese innovation may also be limited by the relative lack of intellectual property protection, discouraging entrepreneurs from breaking new ground.

The 13th International Conference on Ubiquitous Computing, in Beijing in September, left American technology experts underwhelmed.

"There was nothing that really leaped out at me," said John Seeley Brown, who directed the Xerox Palo Alto Research Center in the 1980s, when the concept was invented.

In contrast, he said, he observed true innovation at companies like Foxconn, the Taiwanese manufacturing firm with extensive operations in mainland China that has done much of Apple's assembly work.

"There is the deep embedding of the research and design culture driving a place like Foxconn to do things that they would never have done on their own," he said. "We've now combined the best thinkers in the U.S. sitting side by side with the people who are best at manufacturing in the world."

Still, other investors have glimpsed similar possibilities in China itself. Ruby Lu, a Beijing-based partner in DCM, a venture capital firm with investments in China, described a semiconductor firm begun with lead designers in San Diego and support engineers in Shanghai, working at one-sixth the cost.

"It was the Shanghai team who came up with a groundbreaking solution to an existing problem," she recalled in an e-mail. What scares competitors is that China has begun producing waves of amazing hardware engineers and software programmers, winning international competitions and beginning to dominate the best engineering programs in the United States. The University of California, Berkeley, is about to announce a deal to create an engineering campus in Shanghai, raising fears about transferring technology from one of the best American engineering schools.

Much has been made of computer science "returnees," most notably Andrew Chi-Chih Yao, who left Princeton to create an institute at Tsingtao University in Beijing that has already made breakthroughs in game theory and computer security.

"Overnight there is lots of activity coming from Beijing," said Christos Papadimitriou, a computer scientist at Berkeley.

And there is little question that the structure of Chinese industry is becoming more innovation-oriented. This summer Dieter Ernst, senior fellow at the East-West Center, testified before a Congressional commission that the Chinese had overtaken South Korea and Europe in total patents and were catching up with the United States and Japan.

Moreover, China is now the world's second-largest venture capital market, growing to $7.6 billion from just $2.2 billion in 2005, while the American venture capital market has remained largely stagnant, according to Rebecca A. Fannin, author of the new book "Startup Asia" (Wiley).

Researchers at the Stanford Program on Regions of Innovation and Entrepreneurship recently mapped the investment activity of 769 firms investing in 2,203 Chinese companies and found patterns reminiscent of Silicon Valley.

"You have lead individuals and firms that have established beachheads of success and power," said Marguerite Gong Hancock, a professor at the Stanford Graduate School of Business, who directed the study. "They are the same firms that were successful in Silicon Valley that have transplanted their expertise to China."

The similarities to Silicon Valley can be eerie. "All the symptoms of a bubble are here," said Anne Stevenson-Yang, co-director of J Capital Research, a technology investment research firm in Beijing. "It's an unsettling instability."

At the same time, there is a consensus that China's entrepreneurs have a workaholic culture that is unmatched anywhere in the world.

"What I found in doing five startups in China is the culture makes Silicon Valley look laid-back and slow," said Tom Melcher, an entrepreneur who left California a decade ago to move to Beijing. "In Beijing, if you want to find a chief executive at 7:30 p.m. on a Friday, it's guaranteed you will find him at the office."

Not every China specialist buys such comparisons.

"When we look at China through the lens of American decline, we see the Chinese ascendancy, we see the modern skylines and the fastest computers and the new airports, and we see an invincible force building," said Orville Schell, director of the Center on U.S.-China Relations at the Asia Society. "Through Chinese eyes it looks tremendously uncertain and provisional. They are not filled with self-confidence."

But Mr. McGovern, the investor and venture capitalist, thinks that may be an advantage. In the United States, he says, he is often approached by overconfident entrepreneurs who walk off in a huff when he is less than impressed by their ideas.

The Chinese entrepreneurs he deals with are different.

"They will come to me and show me their language-translation software that will convert Mandarin to English and back again," he said. "Then I will tell them that I don't think there is a market because it is too difficult to protect the intellectual property."

Rather than send them away, however, he might ask them if they would be interested in working on a different idea that his firm has been considering.

"They will respond, 'Can I get rich?' When I tell them that I think that there is a good chance, they say, 'O.K., I'll do it!'"

David Barboza reported from Beijing and John Markoff from San Francisco.

ESSAY **DREW ENDY** *Bioengineering, Stanford*

Taking Faster and Smarter to New Physical Frontiers

The value of computers is often measured with terms like gigahertz, petaflop and exabyte — the speed, scale and efficiency with which they perform computations.

But so what? The intrinsic worth of computation ought to be a matter of the types of information being computed upon, and of when and where these computations occur. When you are lost, for example, a phone that will compute your route home is worth far more to you than an inaccessible desktop PC, no matter how fancy and powerful.

So a better way to think about the future of computing might be to ask when and where we could improve our ability to compute upon information that we greatly care about.

Consider a simple "computer" that counts to just 256, using eight bits of data storage. Could such a computer have any significant value?

Well, what if such computers could be installed inside every cell of your body? What if these computers were used to keep track of how many times each of your cells divided, forming the basis of systems that could track and control aging, development and cancer? If too many divisions are detected, programmed cell death could be set off before a tumor had a chance to form.

Such computers would have incredible value for basic research and medical biotechnology. But note that these computers would derive all their value from being able to connect with and compute inside living cells, a place that no silicon-based computer can now operate.

So would it be possible to build simple computers that operate inside living cells or other new places? Yes — though in the case of biology, such computers would most likely need to be engineered from biological molecules.

Fortunately, sustained basic research since the early 1980s has taught us how natural biological systems might be adapted to store information and compute upon it. Now, researchers are starting to systematically apply this knowledge to develop scalable living data storage systems and simple computational interfaces.

For example, digital information can be stored inside cells by flipping DNA sequences back and forth or by controlling protein levels and locations. In more detail, a DNA sequence that can be switched between two possible orientations can be used to represent and store "0" in one orientation and "1" in the other, which taken together represent one bit.

Other research is exploring how RNA, for example, can be engineered to control the reading and writing of information to synthetic biological bits. But we are still a long way from achieving a reliable genetically encoded eight-bit counter.

When and where else might we find new places to compute upon information? Obviously, improved access to information and computation in many human and cultural systems will be important, from seemingly mundane advances in conference room scheduling or building ventilation to improved medical and political decision-making systems.

But most such futures are foreseeable; they will be based on traditional computing architectures and engineered silicon, and they are likely to be limited by an array of human factors: for example, who controls the room-scheduling system? Who gets access, and how can access be better scaled?

I dream of much broader achievements. For example, suppose we could partner with microbes and plants to record events, natural or otherwise, and convert this information into easily observed signals. That would greatly expand our ability to monitor the environment. And I imagine foods that tell us whether they are organic just by looking at them.

So the future of computing need not only be a question of putting people and things together with ubiquitous silicon computers. The future will be much richer if we can imagine new modes of computing in new places and with new materials — and then find ways to bring those new modes to life.

IN THE LAB From left, Fred Ford, Jorge Heraud and Lee Redden worked on the prototype of a farming robot.

TRAINING Blue River Technology, a start-up company, is teaching its robot to tell crops from weeds.

PHOTOGRAPHS BY RAMIN RAHIMIAN FOR THE NEW YORK TIMES

With a Leaner Model, Start-Ups Reach Further Afield

By STEVE LOHR

SUNNYVALE, Calif. — Lee Redden, 26, a Ph.D. student in engineering at Stanford, recently decided to shelve his education and help found a start-up company. His skills lie in a couple of red-hot niches of artificial intelligence, computer vision and machine learning. Yet he is not applying his talents to Internet search, online commerce or intelligence surveillance.

Mr. Redden's ambitions are further afield — in farm fields, actually. His company, Blue River Technology, is developing a robotic weed killer for organic farms, which shun chemical pesticides. The new venture, he said, is "a great way to bring this technology to agriculture."

The start-up here points to the latest stage of evolution in Silicon Valley, the world's epicenter of innovation. Over the years, the region has shown an unmatched economic dexterity in jumping from one industry of opportunity to another, from military electronics to silicon wafers to personal computers to the Internet.

But the business of the Valley today is less about focusing on a particular industry than it is about a continuous process of innovation with technology, across a widening swath of fields. The trend reflects the steady march of that most protean of technologies — computing — as it makes further inroads into every scientific discipline and industry. Clean technology, bioengineering, medical diagnostics, preventive health care, transportation and even agriculture are part of the mix these days for the Valley's technologists and entrepreneurs.

The pace of discovery has quickened, not only for technologies but also for the process of finding out what companies will succeed.

"What's different in the Valley is that we've found a quasi-scientific method for reinventing businesses and industries, not just products," said Randy Komisar, a partner in a leading venture capital firm, Kleiner Perkins Caufield & Byers, and a lecturer on entrepreneurship at Stanford University. "The approach is much more systematic than it was several years ago."

The newer model for starting businesses relies on hypothesis, experiment and testing in the marketplace, from the day a company is founded. That is a sharp break with the traditional approach of drawing up a business plan, setting financial targets, building a finished product and then rolling out the business and hoping to succeed. It was time-consuming and costly.

The preferred formula today is often called the "lean start-up." Its foremost proponents include Eric Ries, an engineer, entrepreneur and author who coined the term and is now an entrepreneur in residence at the Harvard Business School, and Steven Blank, a serial entrepreneur, author and lecturer at Stanford.

The approach emphasizes quickly developing "minimum viable products," low-cost versions that are shown to customers for reaction, and then improved. Flexibility is the other hallmark. Test business models and ideas, and ruthlessly cull failures and move on to Plan B, Plan C, Plan D and so on — "pivoting," as the process is known.

The National Science Foundation is betting on the new model to improve the rate of commercialization of the university research it finances. In October, the foundation announced the first series of grants for what it calls the N.S.F. Innovation Corps. The 21 three-member teams selected from across the country will receive $50,000 each for six months to test whether their inventions are marketable. It begins with a swing through Stanford and courses taught by Mr. Blank and others, followed by online classes and mentoring. Each team is expected to constantly test its ideas and products with customers, to experiment again and again, adhering to the lean start-up formula.

"It's all about how to apply the scientific method to market-opportunity identification," said Errol B. Arkilic, a program manager at the foundation. "And that is exactly why this method is the one the N.S.F. selected."

Mr. Arkilic, who worked for seven years as an engineer at start-ups in the Valley before joining the government, says that the foundation plans to award 15 or 20 Innovation Corps grants every quarter. "We can't replicate Silicon Valley elsewhere," he said. "But we need to figure out a way to take some of the best practices in Silicon Valley and deploy them elsewhere."

The Valley's lean start-up model is influencing mainstream business education. At business schools, courses on entrepreneurship and entrepreneurial management have been around for years. But this spring, the 900 first-year students at the Harvard Business School

Continued on Page D4

How We Got Here

Milestones in the history of computing, compiled by Nicholas Bakalar.

FROM PEBBLES TO GEAR WHEELS

c. 300 B.C. Oldest abacus, from Babylonia, used pebbles to represent numbers.

c. 150-100 B.C. The Antikythera mechanism, used to make astronomical calculations.

1492 Leonardo da Vinci draws a 13-digit cog wheel adder.

1617 John Napier invents an alternative to the log table, called Napier's Bones.

1622 William Oughtred places log scales side by side and slides them. The slide rule would be widely used for 300 years.

1642 Blaise Pascal invents the Pascaline, an adding machine that uses rotating gear wheels.

Vast and Fertile Ground in Africa for Science to Take Root

By G. PASCAL ZACHARY

He might have been content simply to teach thousands of university students in Uganda how to use computers, assemble them into networks, manage them and write basic software programs. In a poor African country with one of the world's fastest-growing populations and rising Internet use, that alone would have been an enormous achievement.

But Venansius Baryamureeba had bigger ideas. In 2005, when he returned home with a doctorate from the University of Bergen in Norway, he was just one of a handful of computer scientists in Uganda. And his timing was right. The largely agricultural economy had been growing by about 7 percent annually, propelling an enormous expansion of the upper middle class and the urban elite's aspirations for advanced training in science and engineering.

Emboldened by Uganda's relative peace and prosperity, Dr. Baryamureeba founded a new college that includes departments of computer science and computer engineering at creaky Makerere University, in Uganda's capital, Kampala. At the top of a hill near the university's entrance, overlooking the derelict law school to one side and a derelict school mosque to the other, two gleaming glass buildings went up seemingly without a hitch. So many undergraduates swarmed them that the faculty held classes at midnight to accommodate them.

Dr. Baryamureeba wanted more than a vocational school; he also created a graduate program he hoped would someday turn out dozens of Ph.D. scientists who would themselves become college professors and help push the boundaries of global research.

Improbably, his vision is gaining traction at Makerere. Young homegrown scientists there are now nearing completion of their Ph.D.'s. And faculty members are carrying out cutting-edge experiments. They are seeking to endow cellphones with the "intelligence," embedded in tiny software programs animated by mathematical algorithms, to identify diseases in crops or malaria in a person's bloodstream.

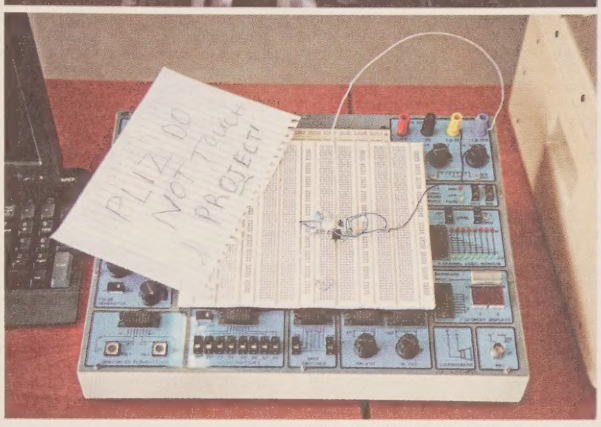
Ernest Mwebaze, a doctoral student and lecturer, said there are still serious obstacles to pursuing such research in Uganda, including unreliable Internet service and power failures. But he also said the potential upside is huge.

"Uganda offers several unique research challenges and problems whose solutions can actually have a greater marginal benefit than, say, solutions to problems in Europe," he said.

Each Monday, in a laboratory of thrumming computers, Mr. Mwebaze teaches a small class on artificial intelligence to 10 graduate students, highlighting this esoteric field, the subject of his doctorate research.

And the potential for Africans trained in Africa to conduct science attuned to the realities of Africa is not limited to computing. "There's a growing interest in research, and science generally, in the region," said Calestous Juma, a Harvard professor who specializes in the study of technology and development.

Josh Kron contributed reporting from Kampala, Uganda.



PHOTOGRAPHS BY TADEJ ZNIDARCIC FOR THE NEW YORK TIMES

UGANDA A classroom and a student project at the new computer science college at Makerere University in the capital, Kampala. A Ph.D. program has also begun.

The rapid spread of cellphones has fueled an appreciation among Africans for the practical uses of science and technology. And the children of the African elite are also seeing career possibilities in computing science and engineering, beyond the traditional disciplines of medicine, law and finance or the more typical scientific callings of crop and soil science.

"Computer science appeals to a generation of urban students raised on a diet of digital devices," said Chanda Chisala of Zambia Online, a software development company and Internet provider in the Zambian capital, Lusaka.

The field also may appeal to chronically underfinanced African universities because the study of computer science is relatively inexpensive. No big atom smashers are needed, as in physics; no giant telescopes, as in astronomy.

Computer science in Africa, to be sure, is still held back by the perception that it is preferable to study and work in Europe or the United States, even if that means leaving Africa permanently. This must change for computer science to flourish in the region. Georgia Tech researchers recommended in a study that African educators reinforce efforts to mold computer science curriculum to meet "local needs."

A shortage of skilled teachers also remains a problem. The continent's leading computer science departments — based on research publications — are all in South Africa. Yet even there, the number of university-level teachers is limited. "Our C.S. departments are much smaller than counterparts in the U.S.," said Bill Tucker, an American who is a senior lecturer at the University of Western Cape.

And differing ethical practices in African and American academic institutions complicate matters. When V. S. Subrahmanian, a computer scientist at the University of Maryland, decided to forge a research partnership last year with Nigerian professors, he was enthusiastically received. But when he provided a Nigerian computer center with data compiled by Maryland, the center started selling it. Dr. Subramanian, who thought the data should have been openly available for scholars, found the experience "very troubling."

Dr. Baryamureeba's commitment has helped Makerere overcome such obstacles. He now leads the entire university, ensuring that computer science and engineering have high-level support. Partnerships with universities in Norway and the Netherlands have also proved crucial. Graduate students from Uganda have been able to study both at home and abroad. And the European universities promise not to poach them, requiring that the students return to Uganda to get their doctorates.

There's also a palpable sense among young scholars that Africa is cool — and that universities are improving just enough to advance the scientific ambitions of Western scientists.

Consider John Quinn, a Scot. He attended Cambridge and received a doctorate in computer science from the University of Edinburgh. Searching for an unconventional research experience, he contacted Makerere just as Dr. Baryamureeba was casting about for international talent to bolster his faculty. Dr. Quinn accepted, and has never looked back. An artificial intelligence research group he formed has received financing from Microsoft and Google. One project involves designing code that turns a cellphone into a sophisticated microscope. He presented his research on diagnosing malaria over the phone at an international conference in San Francisco in August.

"There's a growing awareness of the need to focus, to specialize and to become internationally competitive," Dr. Quinn said of himself and his colleagues.

One potentially practical and profitable benefit partly explains the interest of computer companies in Dr. Quinn's research: Turning cellphones into cheap microscopes and pattern-recognition devices could help people in the developed world lower costs of instant diagnosis of minor medical problems.

So far, Dr. Quinn's reputation has only been enhanced by his work in Uganda, and he's earning decent pay. Postdoctoral salaries for European computer scientists are not that much different from the roughly $3,000 a month Dr. Quinn earns at Makerere. That has him thinking he will stay awhile in Kampala. He'd initially planned to stick it out for two years, but he's now already four years into his African university tenure and sees a lot of running room in computer science — for himself, and for Africa.

ESSAY **SEBASTIAN THRUN** *Developer of Google's self-driving car*

Leave the Driving to the Car, and Reap Benefits in Safety and Mobility

The Jetsons had them in the 1960s. They were the defining element of "Knight Rider" in the 1980s: cars that drive themselves. Self-driving cars appear in countless science fiction movies. By Hollywood standards, they are so normal we don't even notice them.

But in real life, they still don't exist. So what if they were real? What if you could buy one today?

When I was 18, I lost a close friend to a car accident. His friend had taken his father's brand-new Audi Quattro for a spin, and he took my friend along for the ride. On an icy road, the driver lost control of the car and collided head-on with a truck. Both he and my friend were declared dead at the scene.

This was not an isolated occurrence. Roughly a year ago, my lab manager succumbed to a traffic accident. A distracted driver hit her Prius at more than 50 miles an hour from the side while she was driving cautiously through an intersection.

Too many people share the same fate. In 2010, the number of traffic fatalities in the United States was 32,788, according to the Department of Transportation. In recent years, nearly all states have passed laws prohibiting the use of handheld devices while driving. Nevada took a different approach. In a first for any nation, the state passed a law that legalizes texting, provided one does so in a self-driving autonomous car. This places Nevada at the forefront of innovation.

I have been spending the better part of my professional life trying to create self-driving cars.

At Google, I am working with a world-class team of engineers to turn science fiction into reality.

Google's vast computing resources are crucial to our technology. Our cars memorize the road infrastructure in minute detail. They use computerized maps to determine where to drive, and to anticipate road signs, traffic lights and roadblocks long before they are visible to the human eye.

Our cars use specialized lasers, radar and cameras to analyze traffic at a speed faster than the human brain can process. And they leverage the cloud to share information at blazing speed.

Our self-driving cars have now traveled nearly 200,000 miles on public highways in California and Nevada, 100 percent safely. They have driven from San Francisco to Los Angeles and around Lake Tahoe, and have even descended crooked Lombard Street in San Francisco. They drive anywhere a car can legally drive.

I am confident that our self-driving cars will transform mobility. By this I mean they will affect all aspects of moving people and things around and result in a fundamentally improved infrastructure.

Take today's cities. They are full of parked cars. I estimate that the average car is immobile 96 percent of its lifetime. This situation leads to a world full of underused cars and occupied parking spaces.

Self-driving cars will enable car sharing even in spread-out suburbs. A car will come to you just when you need it. And when you are done with it, the car will just drive away, so you won't even have to look for parking.

Self-driving cars can also change the way we use our highways. The European Union has recently started a program to develop technologies for vehicle platoons on public highways. "Platooning" is technical lingo for self-driving cars that drive so closely together that they behave more like trains than individual cars. Research at the University of California, Berkeley, has shown that the fuel consumption of trucks can be reduced by up to 21 percent simply by drafting behind other trucks. And it is easy to imagine that our highways can bear more cars, if cars drive closer together.

Last but not least, self-driving cars will be good news for the millions of Americans who are blind or have brain injury, Alzheimer's or Parkinson's disease. Tens of millions of Americans are denied the privilege of operating motor vehicles today because of issues related to health or age.

Some of these changes are far out in the future. But I envision a future in which our technology is available to everyone, in every car. I envision a future without traffic accidents or congestion. A future where everyone can use a car.

Sebastian Thrun is a Google Fellow and a research professor at Stanford.

With a Leaner Model, Start-Ups Reach Further Afield

From Page D3

must start a business as a required course. In teams of six students each, they will be given $3,000 and told to create a start-up that pulls in revenue by the end of the semester, explained Thomas R. Eisenmann, a professor who will oversee the program.

Dr. Eisenmann is also a leader of a Silicon Valley immersion program that takes dozens of students there each year for a firsthand look at not only the practices but also the culture of the entrepreneurial hothouse. "Everybody is involved in a start-up," Dr. Eisenmann observed. "It's assumed to be normal behavior, the cool thing to do."

The start-up culture, to be sure, owes much to the Valley's history and the enduring influence of its defining personalities, like Frederick E. Terman. A longtime engineering professor at Stanford who was provost in the 1950s and 1960s, Dr. Terman encouraged his star students to put their ideas to work by starting their own companies. Among them were Bill Hewlett and David Packard, who founded Hewlett-Packard in 1939. Dr. Terman often invested his own money in such start-ups.

"His message was that starting a company was every bit as important as getting your Ph.D.," said Mr. Blank, who lectures at Stanford. "That was heresy in academia."

Most start-ups fail. More than perhaps anyplace else, the Valley's investors and technologists tend to view failure with a certain scientific objectivity, as if setbacks are heuristic tools leading to further research and discovery.

"Over 70 years, this Valley has developed a culture that does not personalize failure," said Mr. Komisar, of Kleiner Perkins. "If you're not corrupt, stupid or lazy, we see failure as learning — learn from it, and reapply it."

That risk-taking and perpetual learning culture is now being applied far beyond computer hardware and software. There are high-profile ventures like Nest Labs, founded by Tony Fadell, a former Apple executive, which has hired more than 100 engineers from Apple, Google, Microsoft and other high-tech companies, and it is backed by a pack of venture capital firms. Its product, introduced in late October, is a reinvention of the thermostat, combining sensors, machine learning and Web technology in a clever, energy-saving device.

Yet the Valley is filled with other, less-prominent start-ups in new fields, including Blue River Technology. Mr. Redden met his fellow founder and the start-up's chief executive, Jorge Heraud, 41, in Mr. Blank's class.

Mr. Heraud, an engineer, had decided to return to Stanford to refresh his career, after working for years as a manager for an agriculture equipment company.

He met up with Mr. Redden, and they jointly recognized the opportunity for applying computer vision and machine learning to agriculture. They explored other ideas, but after talking to potential customers, they settled on killing weeds for organic farming — a fast-growing industry that cannot use pesticides and struggles with labor costs.

In their office in Sunnyvale, they are assembling the machine and training the computer-vision software to distinguish lettuce plants from weeds. Initially, they experimented with laser blasts to kill the weeds, but that proved too costly. Now they plan to use superheated oil (organic, of course).

Their contraption, pulled behind a tractor, must identify weeds and kill them within 200 milliseconds, a formidable but attainable challenge, Mr. Redden says.

If applying computer vision to agriculture is so promising, why are the big farm equipment companies not well ahead?

"This isn't on their radar screen," Mr. Heraud replied. "They aren't putting their heads into computer vision. That's a Silicon Valley technology."

LOOMS TO TELEVISIONS

1801 Joseph Marie Jacquard invents a loom that creates woven cloth patterns based on wooden punch cards.

1822 Charles Babbage invents the Difference Engine, a steam-driven machine that could compute log tables.

c. 1830s Babbage designs the Analytic Engine, which uses conditional logic and programmable punch cards.

c. 1840s Ada Lovelace writes one of the first computer programs—that is, an algorithm encoded for computer processing.

1890 The Hollerith Machine, an electric tabulator, calculates the census in one year, a job that previously took eight years.

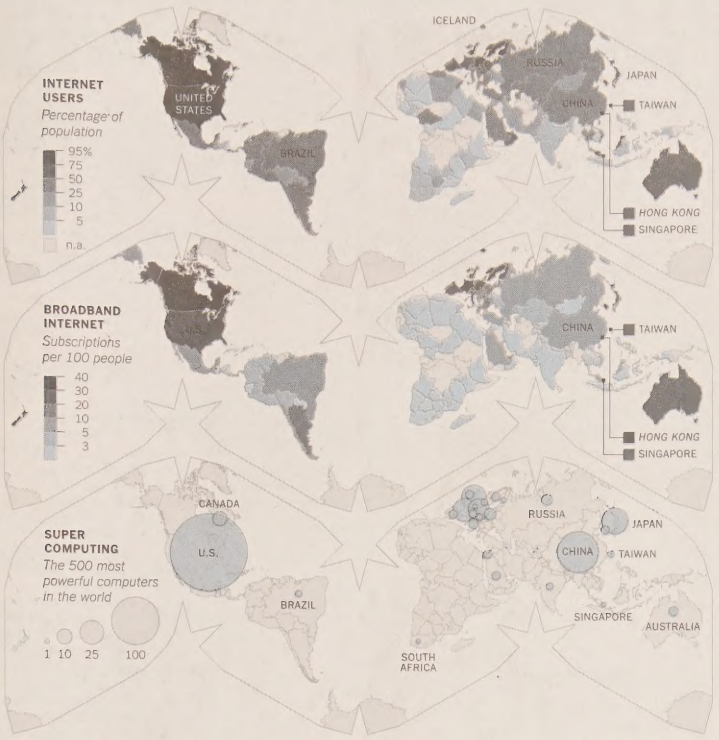
1927 Philo Farnsworth demonstrates the first television.

The Future of Computing

State of the Art

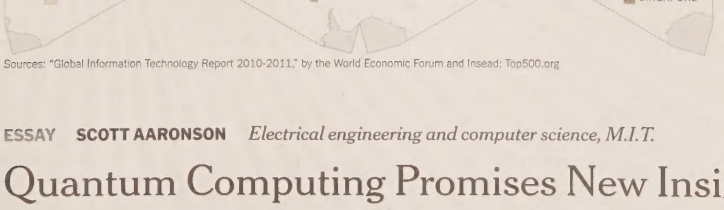
A snapshot of the rapidly changing world of computing, communications and technology.

A GLOBAL INTERNET In just four decades the Internet has spread to much of the world. Now, the shift to high-bandwidth connectivity and the global availability of supercomputing is accelerating.

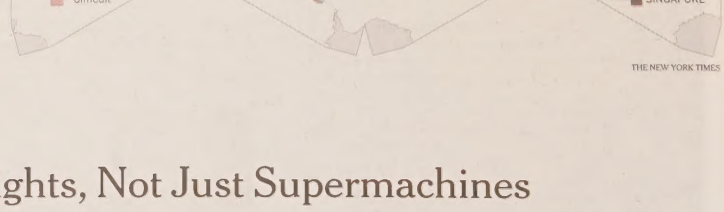


TOWARD AN INNOVATIVE CHINA China is the dominant maker of computers and consumer electronics, and is readily able to adapt and improve on technology innovations made elsewhere. But innovation within the country has been limited by government controls and the relative lack of intellectual property protection.

A MORE CONNECTED WORLD Cellphones are proliferating rapidly in much of the developing world. The use of smartphones and other Internet-connected devices is still low, but should rise quickly in countries like China, which will soon have the world's largest domestic market for Internet commerce and computing.



RAW MATERIALS FOR INNOVATION The synthesis that made Silicon Valley—the concentration of science and engineering talent and venture capital—is now beginning to proliferate in the developing world. China's growing venture capital market is now the second largest in the world.



Sources: "Global Information Technology Report 2010-2011," by the World Economic Forum and Insead; Top500.org

THE NEW YORK TIMES

ESSAY **SCOTT AARONSON** *Electrical engineering and computer science, M.I.T.*

Quantum Computing Promises New Insights, Not Just Supermachines

When people hear that I work on quantum computing — one of the most radical proposals for the future of computation — their first question is usually, "So when can I expect a working quantum computer on my desk?" Often they bring up breathless news reports about commercial quantum computers right around the corner. After I explain the strained relationship between those reports and reality, they ask: "Then when? In 10 years? Twenty?"

Unfortunately, this is sort of like asking Charles Babbage, who drew up the first blueprints for a general-purpose computer in the 1830s, whether his contraption would be hitting store shelves by the 1840s or the 1850s. Could Babbage have foreseen the specific technologies — the vacuum tube and transistor — that would make his vision a reality more than a century later? Today's quantum computing researchers are in a similar bind. They have a compelling blueprint for a new type of computer, one that could, in seconds, solve certain problems that would probably take eons for today's fastest supercomputers. But some of the required construction materials don't yet exist.

So you might think quantum computers are something real scientists — as opposed to science-fiction buffs — won't need to worry about for a long time. But I'd urge a different view. Quantum computing really is one of the most exciting things happening in science right now. Just not for the reasons you usually hear.

First, though, what is a quantum computer? Walk into a quantum computing lab, and you won't see much: maybe a fist-size "trap" where ions (often cadmium or calcium) are suspended in a magnetic field, a laser for moving the ions around, a computer screen with a row of flickering white blobs representing the ions' approximate locations. The real action, one might say, is happening in a different realm entirely: in the alien mathematics that governs what the ions are doing.

Struggling to shoehorn that mathematics into newspaper-friendly metaphors, most popular writers describe a quantum computer as a magic machine that could process every possible answer in parallel, rather than trying them one at a time. Supposedly, it could do that because, unlike today's computers that manipulate bits, a quantum computer would manipulate quantum bits, or qubits, which can be 0 and 1 simultaneously.

But that's a crude way to visualize what a quantum computer does, and misses the most important part of the story. When you measure a quantum computer's output, you see just a single, random answer — not a listing of all possible answers. Of course, if you had merely wanted a random answer, you could have picked one yourself, with much less trouble.

Thus, the sole reason to prefer a quantum computer is that the subatomic world obeys different laws of probability than the ones we are used to. In everyday life, it would be silly to speak of a "minus 30 percent chance of rain tomorrow," much less a "square root of minus 1 percent chance." However, quantum mechanics is based on numbers called amplitudes, which are closely related to probabilities but can also be negative (in fact, they are complex numbers). Crucially, if an event (say, a photon hitting a screen) can happen one way with positive amplitude, and a different way with negative amplitude, then the two amplitudes can "interfere destructively" and cancel each other out, so that the event never happens at all. The goal in quantum computing is to choreograph a computation so that the amplitudes leading to wrong answers cancel each other out, while the amplitudes leading to right answers reinforce.

Contrary to a widespread misconception, it's for only a few specialized types of problem that researchers know how exploit that trick to obtain dramatic speed increases over today's computers. To date, the two main examples are simulating the behavior of atoms and molecules, and breaking certain cryptographic codes — including, by unlucky coincidence, most of the codes used in modern electronic commerce. Of course, both problems can be tackled with conventional computers, too — but, though no one has proved it, it's plausibly conjectured that any conventional algorithm would need a huge amount of time. While code-breaking understandably grabs the headlines, it's the more humdrum application of quantum computers — simulating quantum physics and chemistry — that has the potential to revolutionize fields from nanotechnology to drug design.

Unfortunately, while small quantum computations have already been demonstrated in the lab, they typically fall apart after only a few dozen operations. That's why one of the most-celebrated quantum computations to date has been to factor 15 into 3 times 5 — with high statistical confidence! The problem is decoherence: basically, stray interactions that intrude prematurely on the computer's fragile quantum state, "collapsing" it like a soufflé. In theory, it ought to be possible to reduce decoherence to a level where error-correction techniques could render its remaining effects insignificant. But experimentalists seem nowhere near that critical level yet.

And yet, even though useful quantum computers might still be decades away, many of their payoffs are already arriving. For example, the mere possibility of quantum computers has all but overthrown a conception of the universe that scientists like Stephen Wolfram have championed. That conception holds that, as in the "Matrix" movies, the universe itself is basically a giant computer, twiddling an array of 1's and 0's in essentially the same way any desktop PC does.

Quantum computing has challenged that vision by showing that if "the universe is a computer," then even at a hard-nosed theoretical level, it's a vastly more powerful kind of computer than any yet constructed by humankind. Indeed, the only ways to evade that conclusion seem even crazier than quantum computing itself: One would have to overturn quantum mechanics, or else find a fast way to simulate quantum mechanics using today's computers.

Setting aside these cosmic concerns, there are more practical spinoffs from research in quantum computing. Techniques invented to understand quantum algorithms have repeatedly proved useful for understanding conventional algorithms — and there are now cryptographic codes, purely for conventional computers, for which the main evidence of their security comes from arguments based on quantum computing. Quantum computing ideas have also influenced chemistry and physics: Several research groups have used quantum-computing analogies to explain the remarkable light-harvesting efficiency of photosynthetic molecules in plants, and to suggest how solar panels might be designed with similar efficiencies.

But the biggest payoff so far may have been an improvement in the way quantum mechanics itself is taught and understood. Since its beginnings in the 1920s, quantum mechanics has been considered the prototype of an abstruse, complicated theory: something beyond the grasp of all but a few physicists. Today, though, I and others regularly explain its underlying logic to students by focusing on the simplest imaginable system to which that logic applies: the qubits that make up a quantum computer.

Like fusion power, practical quantum computers are a tantalizing possibility that the 21st century may or may not bring — depending on the jagged course not only of science and technology, but of politics and economics. By contrast, as a scientific endeavor that combines many of the deepest questions of physics and computer science, there's no need to wait for quantum computing: It's already here.

TURING TO SIMON

1937 Alan Turing publishes a description of a "universal computing machine."

1938 Konrad Zuse designs and builds the Z1, the first programmable computer.

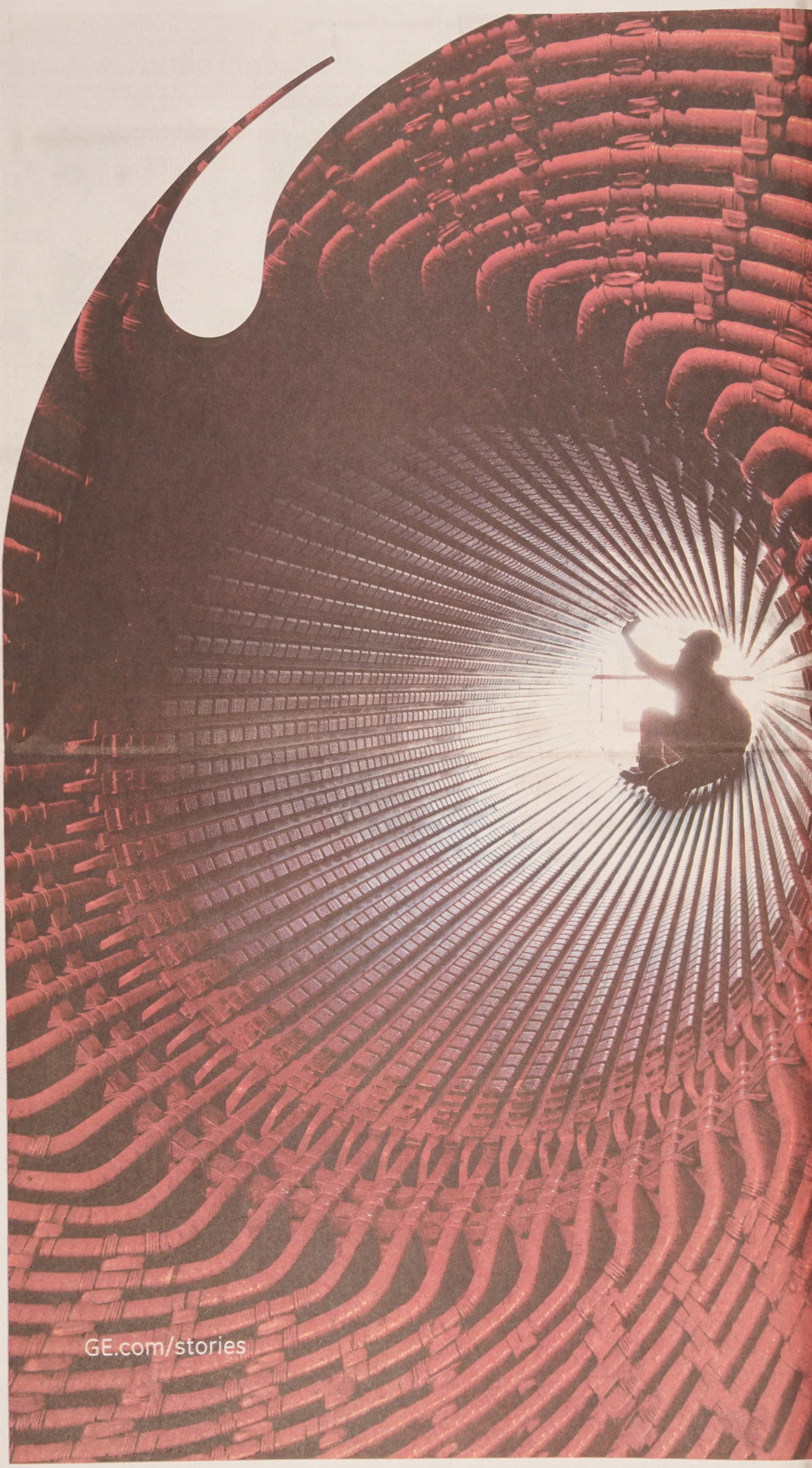
1942 The Atanasoff-Berry Computer is the first electronic digital computer.

1943 Colossus, the first electronic, digital, programmable computer, is used by the British to decode German messages.

1946 Eniac, the Electronic Numerical Integrator and Computer, is the first general-purpose computer.

1949 The Manchester Mark 1, a stored-program computer.

1950 Radio-Electronics magazine publishes plans for the Simon, which some consider the first personal computer.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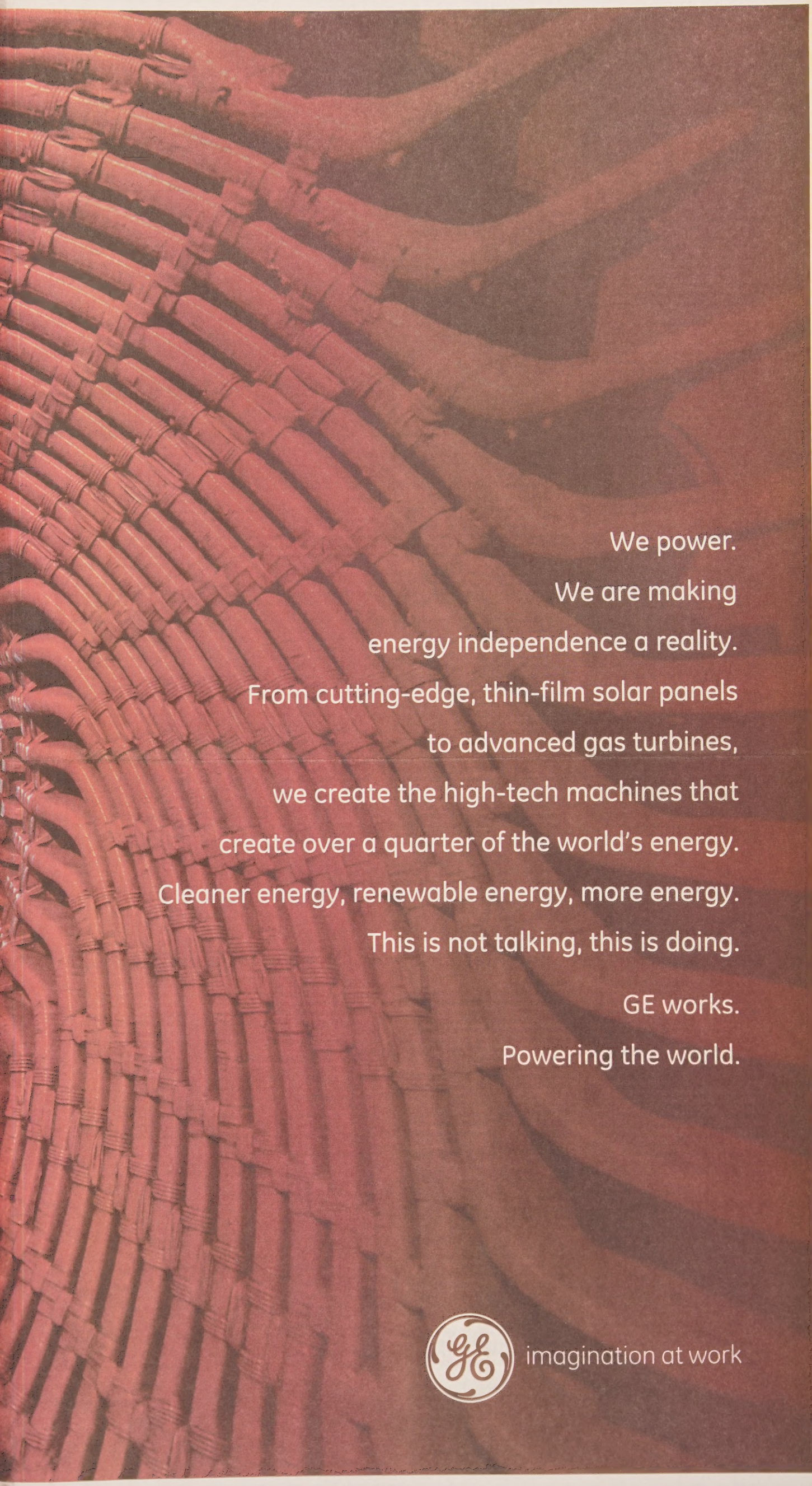

We power.
We are making
energy independence a reality.
From cutting-edge, thin-film solar panels
to advanced gas turbines,
we create the high-tech machines that
create over a quarter of the world's energy.
Cleaner energy, renewable energy, more energy.
This is not talking, this is doing.
GE works.
Powering the world.
imagination at work

Creating Artificial Intelligence Based on the Real Thing

By STEVE LOHR

Ever since the early days of modern computing in the 1940s, the biological metaphor has been irresistible. The first computers — room-size behemoths — were referred to as "giant brains" or "electronic brains," in headlines and everyday speech. As computers improved and became capable of some tasks familiar to humans, like playing chess, the term used was "artificial intelligence." DNA, it is said, is the original software.

For the most part, the biological metaphor has long been just that — a simplifying analogy rather than a blueprint for how to do computing. Engineering, not biology, guided the pursuit of artificial intelligence. As Frederick Jelinek, a pioneer in speech recognition, put it, "airplanes don't flap their wings."

Yet the principles of biology are gaining ground as a tool in computing. The shift in thinking results from advances in neuroscience and computer science, and from the prod of necessity.

The physical limits of conventional computer designs are within sight — not today or tomorrow, but soon enough. Nanoscale circuits cannot shrink much further. Today's chips are power hogs, running hot, which curbs how much of a chip's circuitry can be used. These limits loom as demand is accelerating for computing capacity to make sense of a surge of new digital data from sensors, online commerce, social networks, video streams and corporate and government databases.

To meet the challenge, without gobbling the world's energy supply, a different approach will be needed. And biology, scientists say, promises to contribute more than metaphors. "Every time we look at this, biology provides a clue as to how we should pursue the frontiers of computing," said John E. Kelly, the director of research at I.B.M.

Dr. Kelly points to Watson, the question-answering computer that can play "Jeopardy!" and beat two human champions earlier this year. I.B.M.'s clever machine consumes 85,000 watts of electricity, while the human brain runs on just 20 watts. "Evolution figured this out," Dr. Kelly said.

Several biologically inspired paths are being explored by computer scientists in universities and corporate laboratories worldwide. But researchers from I.B.M. and four universities — Cornell, Columbia, the University of Wisconsin, and the University of California, Merced — are engaged in a project that seems particularly intriguing.

The project, a collaboration of computer scientists and neuroscientists begun three years ago, has been encouraging enough that in August it won a $21 million round of government financing from the Defense Advanced Research Projects Agency, bringing the total to $41 million in three rounds. In recent months, the team has developed prototype "neurosynaptic" microprocessors, or chips that operate more like neurons and synapses than like conventional semiconductors.

But since 2008, the project itself has evolved, becoming more focused, if not scaled back. Its concepts and techniques might be usefully borrowed from biology to push the boundaries of computing, and what cannot be applied, or even understood.

At the outset, Dharmendra S. Modha, the I.B.M. computer scientist leading the project, described the research grandly as "the quest to engineer the mind by reverse-engineering the brain." The project embarked on supercomputer simulations intended to equal the complexity of animal brains — a cat and then a monkey. In science blogs and online forums, some neuroscientists sharply criticized I.B.M. for what they regarded as exaggerated claims of what the project could achieve.

TONY AVELAR/BLOOMBERG NEWS

BIOENGINEERING Dharmendra S. Modha of I.B.M. leads a team developing chips that structurally resemble the brain.

These days at the I.B.M. Almaden Research Center in San Jose, Calif., there is not a lot of talk of reverse-engineering the brain. Wide-ranging ambitions that narrow over time, Dr. Modha explained, are part of research and discovery, even if his earlier rhetoric was inflated or misunderstood.

"Deciding what not to do is just as important as deciding what to do," Dr. Modha said. "We're not trying to replicate the brain. That's impossible. We don't know how the brain works, really."

The discussion and debate across disciplines has helped steer the research, as the team pursues the goals set out by Darpa, the Pentagon's research agency. The technology produced, according to the guidelines, should have the characteristics of being self-organizing, able to "learn" instead of merely responding to conventional programming commands, and consuming very little power.

"We have this fantastic network of specialists who talk to each other," said Giulio Tononi, a psychiatrist and neuroscientist at the University of Wisconsin. "It focuses our thinking as neuroscientists and guides the thinking of the computer scientists."

In early 2010, Dr. Modha made a decision that put the project on its current path. While away from the lab for a few weeks, because of a Hawaiian vacation and a bout of flu, he decided to streamline the work of the far-flung researchers. The biologically inspired chip under development would come first, Dr. Modha said. That meant a lot of experimental software already written was scrapped. But, he said, "chip-first as an organizing principle gave us a coherent plan."

In designing chips that bear some structural resemblance to the brain, so-called neuromorphic chips, neuroscience was a guiding principle as well. Brains are low-power, nimble computing mechanisms — real-world proof that it is possible.

A brain does its computing with a design drastically different from today's computers. Its processors — neurons — are, in computing terms, massively distributed; there are billions in a human brain. These neuron processors are wrapped in its data memory devices — synapses — so that the brain's paths of communication are extremely efficient and diverse, through the neuron's axons, which conduct electrical impulses.

A machine that adopts that approach, Dr. Modha said, would represent "a crucial shift away from von Neumann computing." He was referring to a design with processor and memory physically separated and connected by a narrow communications channel, or bus, and operating according to step-by-step sequential methods — the von Neumann architecture used in current computers, named after the mathematician John von Neumann.

The concept of neuromorphic electronic systems is more than two decades old; Carver Mead, a renowned computer scientist, described such devices in an engineering journal article in 1990. Earlier biologically inspired devices, scientists say, were mostly analog, single-purpose sensors that mimicked one function, like an electronic equivalent of a retina for sensing image data.

But the I.B.M. and university researchers are pursuing a more versatile digital technology. "It seems that we can build a computing architecture that is quite general-purpose and could be used for a large class of applications," said Rajit Manohar, a professor of electrical and computer engineering at Cornell University.

What might such applications be, 5 or 10 years from now, if the technology proves successful? They would be the sorts of tasks that humans find effortless and that computers struggle with — the pattern recognition of seeing and identifying someone, walking down a crowded sidewalk without running into people, learning from experience. Specifically, the scientists say, the applications might include robots that can navigate a battlefield environment and be trained; low-power prosthetic devices that would allow blind people to see; and computerized health-care monitors that watch over people in nursing homes and send alerts to human workers if a resident's behavior suggests illness.

It is an appealing vision, but there are formidable obstacles. The prototype chip has 256 neuron-like nodes, surrounded by more than 262,000 synaptic memory modules. That is impressive, until one considers that the human brain is estimated to house up to 100 billion neurons. In the Almaden research lab, a computer running the chip has learned to play the primitive video game Pong, correctly moving an on-screen paddle to hit a bouncing cursor. It can also recognize numbers 1 through 10 written by a person on a digital pad — most of the time. But the project still has a long way to go.

It is still questionable whether the scientists can successfully assemble large clusters of neuromorphic chips. And though the intention is for the machines to evolve more from learning than from being programmed, the software that performs that magic for any kind of complex task has yet to be written.

The project's Pentagon sponsor is encouraged. "I'm surprised that we're so far along, and I don't see any fundamental reason why it can't be done," said Todd Hylton, a program manager.

If it succeeds, the project would seem to make peace with the "airplanes don't flap their wings" critique. "Yes, they are different, but bird wings and plane wings both depend on the same aerodynamic principles to get lift," said Christopher T. Kello, director of the Cognitive Mechanics Lab at the University of California, Merced. "It's the same with this project. You can use essential design elements from biology."

ESSAY **DAPHNE KOLLER** *Stanford Artificial Intelligence Laboratory*

Death Knell for the Lecture: Technology as a Passport to Personalized Education

Our education system is in a state of crisis. Among developed countries, the United States is 55th in quality rankings of elementary math and science education, 20th in high school completion rate and 27th in the fraction of college students receiving undergraduate degrees in science or engineering.

As a society, we can and should invest more money in education. But that is only part of the solution. The high costs of high-quality education put it off limits to large parts of the population, both in the United States and abroad, and threaten the school's place in society as a whole. We need to significantly reduce those costs while at the same time improving quality.

If these goals seem contradictory, let's consider an example from history. In the 19th century, 60 percent of the American work force was in agriculture, and there were frequent food shortages. Today, agriculture accounts for less than 2 percent of the work force, and there are food surpluses.

The key to this transition was the use of technology—from crop rotation strategies to GPS-guided farm machinery — which greatly increased productivity. By contrast, our approach to education has remained largely unchanged since the Renaissance: From middle school through college, most teaching is done by an instructor lecturing to a room full of students, only some of them paying attention.

How can we improve performance in education, while cutting costs at the same time? In 1984, Benjamin Bloom showed that individual tutoring had a huge advantage over standard lecture environments: The average tutored student performed better than 98 percent of the students in the standard class.

Until now, it has been hard to see how to make individualized education affordable. But I argue that technology may provide a path to this goal.

Consider the success of the Khan Academy, which began when Salman Khan tried to teach math remotely to his young cousins. He recorded short videos with explanations and placed them on the Web, augmenting them with automatically graded exercises. This simple approach was so compelling that by now, more than 700 million videos have been watched by millions of viewers.

At Stanford, we recently placed three computer science courses online, using a similar format. Remarkably, in the first four weeks, 300,000 students registered for these courses, with millions of video views and hundreds of thousands of submitted assignments.

What can we learn from these successes? First, we see that video content is engaging to students — many of whom grew up on YouTube — and easy for instructors to produce.

Second, presenting content in short, bite-size chunks, rather than monolithic hourlong lectures, is better suited to students' attention spans, and provides the flexibility to tailor instruction to individual students. Those with less preparation can dwell longer on background material without feeling uncomfortable about how they might be perceived by classmates or the instructor.

Conversely, students with an aptitude for the topic can move ahead rapidly, avoiding boredom and disengagement. In short, everyone has access to a personalized experience that resembles individual tutoring.

Watching passively is not enough. Engagement through exercises and assessments is a critical component of learning. These exercises are designed not just to evaluate the student's learning, but also, more important, to enhance understanding by prompting recall and placing ideas in context.

Moreover, testing allows students to move ahead when they master a concept, rather than when they have spent a stipulated amount of time staring at the teacher who is explaining it.

For many types of questions, we now have methods to automatically assess students' work, allowing them to practice while receiving instant feedback about their performance. With some effort in technology development, our ability to check answers for many types of questions will get closer and closer to that of human graders.

Of course, these student-computer interactions can leave many gaps. Students need to be able to ask questions and discuss the material. How do we scale the human interaction to tens of thousands of students?

Our Stanford courses provide a forum in which students can vote on questions and answers, allowing the most important questions to be answered quickly — often by another student. In the future, we can adapt Web technology to support even more interactive formats, like real-time group discussions, affordably and at large scale.

More broadly, the online format gives us the ability to identify what works. Until now, many education studies have been based on populations of a few dozen students. Online technology can capture every click: what students watched more than once, where they paused, what mistakes they made. This mass of data is an invaluable resource for understanding the learning process and figuring out which strategies really serve students best.

Some argue that online education can't teach creative problem-solving and critical-thinking skills. But to practice problem-solving, a student must first master certain concepts. By providing a cost-effective solution for this first step, we can focus precious classroom time on more interactive problem-solving activities that achieve deeper understanding — and foster creativity.

In this format, which we call the flipped classroom, teachers have time to interact with students, motivate them and challenge them. Though attendance in my Stanford class is optional, it is considerably higher than in many standard lecture-based classes. And after the Los Altos school district in Northern California adopted this blended approach, using the Khan Academy, seventh graders in a remedial math class sharply improved their performance, with 41 percent reaching advanced or proficient levels, up from 23 percent.

A 2010 analysis from the Department of Education, based on 45 studies, showed that online learning is as effective as face-to-face learning, and that blended learning is considerably more effective than either.

Online education, then, can serve two goals. For students lucky enough to have access to great teachers, blended learning can mean even better outcomes at the same or lower cost. And for the millions here and abroad who lack access to good, in-person education, online learning can open doors that would otherwise remain closed.

Nelson Mandela said, "Education is the most powerful weapon which you can use to change the world."

By using technology in the service of education, we can change the world in our lifetime.

UNIVAC TO ATARI

1951 Univac I, the Universal Automatic Computer, is the first commercial computer produced in the U.S.

1951 Whirlwind, the first computer with a video display.

1952 The IAS machine, developed by John von Neumann.

1960 The PDP-1 runs history's first game on a minicomputer: Spacewar!

1969 Arpanet, the first computer network.

1971 Computer Space, first video arcade game.

1971 Intel produces the first microprocessor, the 4004.

1972 Nolan Bushnell and Ted Dabney start Atari Computers.

Out of a Writer's Imagination Came an Interactive World

By JOHN SCHWARTZ

Neal Stephenson doesn't like talking about how he predicted the future.

Mr. Stephenson is the author of a baker's dozen novels whose dazzling range includes rocket-propelled thrillers and a vast historical epic known as the Baroque Cycle, which takes place at the dawn of modern science in the time of Newton and Leibniz.

His reputation for prescience is well earned, even if he regards it lightly. His third novel, "Snow Crash," was published way back in ancient 1992 and laid out many of the attributes of today's online life, including the Metaverse, a virtual place where people meet, do business and play, presenting themselves as avatars. If you've ever played wildly popular multiplayer online games like World of Warcraft, or visited the virtual communities of Second Life, you can get a chill thinking about what he saw back before the popularization of the World Wide Web.

The title of seer falls to novelists now and then: William Gibson got it in the early 1980s for works envisioning cyberspace; more recently, Gary Shteyngart picked it up for the eerie elements of a future foretold, including people's total reliance on their "apparat" smartphones in his novel "Super Sad True Love Story."

Asked to join in a conversation about the future of computing grounded, in part, in that sense that many of us are living in a world he envisioned, Mr. Stephenson, 52, responded with the e-mail equivalent of a sigh.

Politely, but with a suggestion of weariness, he wrote: "Thanks for thinking of me, but this is actually just about my least favorite interview topic of all time. I'm not sure why."

He added, "It seems reasonable, but I just can't find the joy in talking about how I allegedly 'foretold' stuff." He then agreed to the interview anyway, to coincide with a trip to New York.

Over lunch at the Omni Berkshire Place hotel in Manhattan, he explained his reticence about taking credit for clairvoyance. For one thing, he said, it isn't really true. "The way the Internet developed, in my mind, is completely different from the Metaverse in 'Snow Crash,'" he said. "I can talk all day long about how wrong I got it. But there are a lot of people who feel as though that was an accurate prediction."

He described his reputation as a seer in terms resembling what psychologists call the focusing illusion — too much attention to some aspects of a thing and too little to others. Science fiction writers are "shotgunning ideas" through their works, he said, and people tend to recall the pellets that hit the target. "The perception of goodness is just selective," he said.

He suggested that the near-reverence for writerly efforts at prognostication — and Mr. Stephenson's many fans can be disconcertingly passionate — are downright goofy in light of the fact that "there must be countless billions of dollars that go every year into really systematic and motivated future-predicting activities."

Of course, those systematic and well-financed efforts can fail spectacularly, as when the intelligence community failed to anticipate India's test of nuclear bombs in 1974. Remember those Iraqi weapons of mass destruction?

PREQUEL Before the invention of the Web, Neal Stephenson saw the Metaverse, a virtual place for people to meet.

The thought receives a sardonic grin in reply.

Regardless of whether he foresaw the future, he did foresee the world he would create in his most recent novel, Reamde, a 1,056-page return to the thriller genre after years of weightier fare like the Baroque Cycle.

Its protagonist, Richard Forthrast, is a one-time marijuana smuggler who becomes the creator of a successful multiplayer online game, T'Rain. There are hackers who unleash a malicious computer program (the titular Reamde) and set in motion a swirling plot that involves Russian mobsters, British and American agents, Chinese hackers and Forthrast's niece Zula and her hacker boyfriend. A tag line for the novel on Mr. Stephenson's Web site reads, "When the virtual game becomes real, you win or you die."

Which is also a great line from George R. R. Martin's "Game of Thrones," but let's let the folks in marketing thrash that one out.

This use of the vast resources of a networked world to play games with mortal stakes is a central element of the world that Mr. Stephenson laid out in books like "Snow Crash," and in another of his novels, "The Diamond Age: Or, a Young Lady's Illustrated Primer." That book, published in 1995, described in detail an interactive book that can teach lessons on many topics, entertain with games and provide virtual training for living in the real world.

And the notion of learning real-world skills from online gaming is also a big theme of "Reamde," in which young Chinese hackers hone their skills in English, learn effective problem-solving skills, even jury-rig a sail for a motorboat that has run out of fuel.

When he was asked, toward the end of lunch, where he thought computing might be headed, he paused to rephrase the question. "I'll tell you what I'd like to see happen," he said, and began discussing what the future was supposed to have looked like, back in his 1960s childhood. He ticked off the tropes of what he called "techno-optimistic science fiction," including flying cars and jetpacks. And then computers went from being things that filled a room to things that could fit on a desk, and the economy and industries changed. "The kinds of super-bright, hardworking geeky people who, 50 years ago, would have been building moon rockets or hydrogen bombs or what have you have ended up working in the computer industry, doing jobs that in many cases seem kind of ignominious by comparison."

Again, a beat. A consideration, perhaps, that he is talking about the core readership for his best sellers. No matter. He's rolling. He presses on.

"What I'm kind of hoping is that this is just kind of a pause, while we assimilate this gigantic new thing, ubiquitous computing and the Internet. And that at some point we'll turn around and say, 'Well, that was interesting — we have a whole set of new tools and capabilities that we didn't have before the whole computer/Internet thing came along.'"

He said people should say, "Now let's get back to work doing interesting and useful things."

The needs of the world are great: New forms of energy, space transportation and infrastructure all need to be tackled with imagination and innovation, he said. He grew animated as he discussed his latest initiative: He is now pushing for a return to a can-do American culture that can "get big stuff done."

He is trying to carve out a place for science fiction to help by, well, predicting the future. Wait, that's not quite it: He wants science fiction to help by creating the future — supplying the imagination and inspiration to the next generation of engineers and scientists, just as writers like Stanislaw Lem helped inform and usher in the space age. And as he might have done by giving engineers a vision of the Metaverse, though he doesn't say that part out loud.

He is doing it through Hieroglyph, a project of writers who hope to reignite the popular imagination to "develop new technologies and implement them on a heroic scale," as he put it in a recent essay in World Policy Journal, with fiction that returns to its techno-optimistic roots.

The tools of computing and a networked world can help to get us there, he said, but only if we use our newfound power as a means to those ends, instead of as ends in themselves.

"We can't Facebook our way out of the current economic status quo."

ESSAY **LARRY SMARR** *Founding director, Calit2*

An Evolution Toward a Programmable Universe

Over the next 10 years, the physical world will become ever more overlaid with devices for sending and receiving information.

Already billions of processors are embedded in our smartphones, cars, appliances and buildings and the environment. These sensors can send out streams of data about their surroundings, and more and more it is anonymously transmitted to remote data centers — the "clouds" of Google, Amazon, Microsoft, Yahoo and Apple.

From these vast clouds, the companies can power apps that are "spatially aware." For instance, Google Maps now draws on data in the cloud to sample the location and movement of cellphones in cars, producing a real-time picture of traffic congestion.

Smart electric grids are measuring our homes' use of power; active people are tracking their heart rates; and hundreds of millions of us are uploading geo-tagged data to Flickr, Yelp, Facebook and Google Plus. As we look 10 years ahead, the fastest supercomputer (the "exascale" machine) will be composed of one billion processors, and the clouds will most likely grow to this scale as well, creating a distributed planetary computer of enormous power.

Such computational power, co-located with the gigantic storage that holds the data from all the incoming data streams, will enable faster-than-real-time simulations of many aspects of our physical world. As Mike Liebhold and his colleagues at the Institute for the Future have discussed, computing will have evolved from merely sensing local information to analyzing it to being able to control it. In this evolution, the world gradually becomes programmable.

At the California Institute for Telecommunications and Information Technology, we are using this vision to better understand the coming digital transformation of health, energy, environment and culture. We are experimenting with sensors to monitor electricity use in homes, buildings and data centers; the data can then be analyzed and used to control lighting, heating, cooling, appliances and computers to make them more energy-efficient.

It is logical that the analysis of traffic data, coupled with in-car radar and autopilot electronics, will enable software control of large numbers of robot-driven electric cars. Since buildings and transportation are major sources of greenhouse gas emissions, the sensor-aware planetary computer can be a crucial factor in reducing our carbon footprints.

The same principle applies to our bodies. I wear sensors to measure my steps, caloric burn and sleep patterns, while heart patients can wear sensors that wirelessly notify their doctors of life-threatening conditions. People will soon be able to have their genetic code and medical imaging stored in the cloud, along with charts of vital signs and detailed nutritional analysis of everything they consume.

Using this data, the planetary computer will be able to build a computational model of your body and compare your sensor stream with millions of others. Besides providing early detection of internal changes that could lead to disease, cloud-powered voice-recognition wellness coaches could provide continual personalized support on lifestyle choices, potentially staving off disease and making health care affordable for everyone.

Finally, in culture, the fine-grain streaming provided by Twitter, Facebook and Google Plus enables us to map out phenomena using "human sensors."

For instance, a vast power failure occurred in Southern California in September; within minutes we could tell from the locations of Twitter messages saying "my power just went out" that it was widespread, long before the official announcement. Similarly, Twitter feeds from large geographic areas have been analyzed to create dynamic "social mood" or "political anger" maps, like the Google traffic maps constructed from GPS feeds.

Conceivably, the coupling of the sensor and human streams with planetary computing power will make it possible to create "social forecasts." For good or evil, it seems inevitable that individuals, corporations, political leaders and intelligence agencies will come to use planetary computer models of social behavior to inject content into the global attention stream at just the right moment, hoping to steer the social dynamics to a desired outcome.

With the continuing exponential increase in the power of the planetary computer, one has to wonder whether we stand at the beginning of what Isaac Asimov's "Foundation" series, more than 60 years ago, called "psychohistory." His visionary genius Hari Seldon believed that statistical forecasting of human society's actions would be possible with data from enough people throughout the galaxy.

In the next several decades, we will have a glimpse of whether something similar can emerge on planet Earth.

ESSAY **JOICHI ITO** *Director, M.I.T. Media Lab*

In an Open-Source Society, Innovating by the Seat of Our Pants

The Internet isn't really a technology. It's a belief system, a philosophy about the effectiveness of decentralized, bottom-up innovation. And it's a philosophy that has begun to change how we think about creativity itself.

Almost 20 years ago, I installed on my computer a tiny piece of software called MacPPP, which connected the programs running on it to the Internet. The program immediately transformed my computer from a fancy telex machine to a device running a very early version of the graphical Web.

I was working in entertainment at the time, and I remember thinking that this connection was going to change everything. I left to join the first commercial Internet service provider in Japan, PSINet Japan, as its first chief executive. Our first serious challenge, oddly enough, was a battle over an obscure information-sharing computer protocol called X.25. Most of us laboring to build the new Internet preferred the less regulated and simpler Internet Protocol.

Until then, large intergovernmental agencies had always gathered experts to work on the technical standards that would become the DNA of the telecommunications industry, the standards to which all companies would have to build their networks and products. These researchers had produced X.25, a complex and extremely well-considered standard that seemed to anticipate every possible problem and application.

The Internet, on the other hand, was designed and deployed by small groups of researchers following the credo of one of its chief architects, David Clark: "rough consensus and running code." Its early standards — uncomplicated, consensual — were stewarded by small organizations that resisted permission or authority. And they won: The Internet Protocol on which every connected device relies was a triumph of distributed innovation over centralized expertise.

The ethos of the Internet is that everyone should have the freedom to connect, to innovate, to program, without asking permission. No one can know the whole of the network, and by design it cannot be centrally controlled. This network was intended to be decentralized, its assets widely distributed. Today most innovation springs from small groups at its "edges."

This technical strategy has led to the creation of a gigantic network of far-flung innovators who develop standards with one another and share the products of their work in the form of free and open-source software. The architecture of the Internet and its abundance of free software and components has driven down the cost of manufacturing, distribution and collaboration — of innovation. It used to cost millions of dollars to start a software company. Today, for little or no money, entrepreneurs are able to develop and release a "minimum viable product" and test it with real users on the Internet before they have to raise any money from investors. In their earliest iterations, Facebook, Yahoo and Google were running in dorm rooms and labs before the founders had left college or had raised outside money.

In fact, it is now usually cheaper to just try something than to sit around and try to figure out whether to try something. The product map is now often more complex and more expensive to create than trying to figure it out as you go. The compass has replaced the map, and "rough consensus and running code" has become the fundamental philosophy for the so-called lean start-up movement.

Innovators are able to prototype a new product with 3-D printers and cheap laser cutters for nearly nothing. Even complex products can be manufactured with help from supply chain companies that are making their systems available online to anybody. Today we are seeing the emergence of a community of hardware hackers and designers very reminiscent of the developers who wrote the original open standards of the Internet. An explosion of grass-roots innovation in hardware is coming — freely designed and freely shared — as it did in software.

What has been a wildly successful model for consumer Internet start-ups in Silicon Valley turns out to be an extremely good model for learning in a wide variety of fields and disciplines. The students at M.I.T.'s Media Lab experiment, create and iterate; they produce demos and prototypes, and share and collaborate with the rest of the world through the Internet and a distributed network of connections and relationships.

I don't think education is about centralized instruction anymore; rather, it is the process establishing oneself as a node in a broad network of distributed creativity.

Neoteny, one of my favorite words, means the retention of childlike attributes in adulthood: idealism, experimentation and wonder. In this new world, not only must we behave more like children, we also must teach the next generation to retain those attributes that will allow them to be world-changing, innovative adults who will help us reinvent the future.

ALTO TO MACINTOSH

1973 Xerox Alto, a desktop computer with a mouse and a graphical user interface.

1974 Radio-Electronics introduces the Mark-8 kit.

1975 Altair 8800 computer, which runs Microsoft Basic.

1976 Steve Jobs and Steve Wozniak begin selling the Apple I for $666. Users had to build their own cases.

1977 The Apple II goes on sale, for $1,295.

1981 IBM unveils the PC.

1984 Apple releases the Macintosh.

The Future of Computing

A High-Stakes Search Continues for Silicon's Successor

By JOHN MARKOFF

STANFORD, Calif. — In a cluttered chip-making laboratory on Stanford's campus, Max Shulaker is producing the world's smallest computer circuits by hand.

Mr. Shulaker, a graduate student in electrical engineering, is helping to pioneer an extraordinary custom manufacturing process: making prototypes of a new kind of semiconductor circuit that may one day be the basis for the world's fastest supercomputers — not to mention the smallest and lowest-powered consumer gadgets.

If the new technology proves workable, it will avert a crisis that threatens to halt more than five decades of progress by chip makers, who now routinely etch circuits smaller than a wavelength of light to make ever more powerful computers.

Even light waves, it turns out, have their limits. In an industry renowned for inventions both radical and resourceful, designers are in urgent need of new ways to make circuits smaller, faster and cheaper.

This year Intel, the world's largest chip maker, introduced a 3-D transistor that pushes a thin pillar out of the plane of the silicon surface, in an effort to accommodate billions of tiny switches on a single microprocessor.

That approach is controversial; the challenge is not just to squeeze in more switches but to get them to turn on and off quickly and cleanly, and many people in the industry believe there are less drastic ways to do that.

And whichever approach proves most effective, there is a growing consensus among engineers and industry executives that silicon's days are numbered. On the horizon is an even smaller manufacturing world, nanoelectronics, that will be characterized by the ability to build circuits on a molecular scale.

So at universities and corporate laboratories around the world, researchers are trying to develop the next generation of chip-making technologies.

Mr. Shulaker is a member of the Robust Systems Group at Stanford, led by Subhasish Mitra, a former Intel engineer. The new switch he and other student researchers are making is called a carbon nanotube field effect transistor, or C.N.F.E.T.

To make prototype switches, Mr. Shulaker first chemically grows billions of carbon nanotubes — each only about 12 atoms wide — on a quartz surface. He coats them with an ultrafine layer of gold, and then uses a piece of tape — much like a lint remover — to pick them up by hand and transfer them gently to a silicon wafer.

The difference is that for the first time circuits are not etched with light waves; rather, they are at least partly "self-assembling." The ultrafine wires made from carbon nanotubes are being laid down using a chemical process as the first step in making a computer circuit.

What results are nanocircuits that are far smaller and use far less power than today's most advanced silicon-based computer circuits.

With the light-etching method, the smallest part of a semiconductor is currently 32 nanometers, and the nanotechnology is an approach that both Intel and I.B.M. have high hopes for by the time semiconductor parts are down to seven nanometers — which could be as early as 2017.

"We're exploring this very seriously," said Supratik Guha, director of physical sciences at I.B.M.'s Thomas J. Watson Research Laboratory. "We feel that if we can place carbon nanotubes a couple of nanometers apart, they will outperform silicon."

The idea of scaling down electronic circuits goes back at least to 1960, when a young electrical engineer named Douglas Engelbart spoke at a radio and electronics technical conference in Philadelphia. Dr. Engelbart had hit on the idea that shrinking the basic circuitry of the first digital computers could lead to a drastic increase in power.

"Boy, are there going to be some surprises over there," he told his audience.

PHOTOGRAPHS BY LIANNE MILTON FOR THE NEW YORK TIMES

THE NEW CIRCUIT Max Shulaker and colleagues grow billions of carbon nanotubes on a quartz surface, then coat them with gold and transfer them to a silicon wafer.

It turned out to be an understatement.

A half decade later, Gordon Moore, then a chemist at Fairchild Semiconductor, formalized the ability of a new technique called photolithography to scale down components, saying it could be done at regular intervals and predicting that it would be exponential — doubling the number of transistors that could be put on a microchip every year.

Moore's Law, as it came to be called, was only a little optimistic: The doubling has taken place every 18 months or so for nearly five decades. Today several billion transistors can fit on a single chip, and the resulting era of microelectronics has transformed the world, touching virtually every aspect of human existence — from African subsistence farmers who can now get market prices via text message to supercomputers that can simulate nuclear explosions and predict climate change.

But with each new generation of technology, the obstacles have grown more imposing, and the cost of surmounting them is going up, not down. For example, the Taiwan Semiconductor Manufacturing Company, one of the world's largest chip makers, expects to spend almost $10 billion on its next factory.

Moreover, as standard CMOS computer circuits pack more and more transistors, they tend to leak electricity — and thus generate excess heat.

The warning signs began a decade ago, when Patrick P. Gelsinger, then Intel's chief technology officer, warned that if the trends continued, microprocessor chips would reach the temperature of the sun's surface by 2011. To prevent that, the company executed what it called a "hard right turn," gaining speed by adding parallel computing capabilities rather than increasing the chips' clock speeds.

Even that approach has its limits, however. This year, researchers at the University of Washington and Microsoft warned of what they called "dark silicon." With so many processors on a single chip, it is impractical to supply power to all of them at the same time. So some of the transistors are left unpowered — dark, in industry parlance.

The new limits are particularly daunting for supercomputer designers, who are looking to build an "exascale" system — 1,000 times the speed of today's fastest computers — by 2019. Using today's components, that would require 10 million to 100 million processors — compared with almost one million today — and would consume more than a billion watts.

At the annual supercomputing conference in Seattle last month, Jen-Hsun Huang, chief executive of Nvidia, a maker of graphics accelerator chips used in game machines and computers, warned that while supercomputing performance had improved one million times in the last two decades, the power needed to run a computer had increased just 40 times. This rate of increase had been predicted by Robert H. Dennard, the I.B.M. electrical engineer who invented the dynamic random access memory, or DRAM, chip. However, in the face of the growing problem of current leakage, the huge benefit, which had offered a constant eight times performance increase per watt, has reached its limit.

"The impact of that small analysis is dramatic over time," Mr. Huang said. "It's fundamental to our industry — this is our gravity."

Mr. Huang's company, which began as a Silicon Valley maker of graphics cards for 3-D video games and has recently begun to offer software that optimizes its processors for scientific and engineering applications, mirrors broader trends in the computer industry.

Until the 1990s, state-of-the-art computing systems began with corporate and military applications. Since then, increasingly the technology has been driven from the bottom up. The vast economies of scale offered by consumer electronics products has dictated that many of the fastest supercomputers are now built from components first designed for consumers.

At this year's supercomputing conference, for example, researchers at the Barcelona Supercomputing Center in Spain announced that they were planning a system based on a new Nvidia chip that combines its graphics processors with the ARM microprocessor that is widely used in smartphones.

Combining graphics processors, microprocessors and other computer components onto single integrated chips is only a stopgap measure, however. Within a few years, experts say, the conventional CMOS transistors will no longer be able to scale down at a Moore's Law pace.

Here at Stanford, Dr. Mitra says a system based on carbon nanotubes may greatly outperform Intel's current 3-D transistor technology. Indeed, it might be possible to stack multiple layers of these carbon switches, creating genuine three-dimensional circuits.

But he acknowledges that carbon nanotube technology "still has its catches."

Other technologies, too, may be contenders in the nanoelectronics sweepstakes.

Researchers at HP Labs have said they are close to commercializing a new semiconductor technology based on a circuit element called a "memristor," which can substitute for transistors, initially in a memory chip that might offer an alternative to both Flash and DRAM memories.

The researchers previously reported in The Proceedings of the National Academy of Sciences that they had devised a new method for storing and retrieving information from a vast three-dimensional array of memristors. The scheme could potentially free designers to stack thousands of switches in a high-rise fashion, permitting a new class of ultradense computing devices even after two-dimensional scaling reaches fundamental limits.

In a recent lecture at Stanford, Stan Williams, a physicist who is leading the effort at HP, said the group was focusing on a new type of semiconducting material, titanium dioxide, which he said could rival silicon.

"Suffice it to say this is not in the deep dark future," he said. "This is not 10 years out."

Dr. Williams said the memristor could have significant power and size advantages over conventional transistors used in logic devices like microprocessors, which must be continually powered to preserve information. By contrast, the HP technology is nonvolatile — it is necessary only to apply power to change the state of the switch and to read its value.

Moreover, like the carbon nanotube design, it lends itself to three-dimensional structures.

"This is something that has been eluding the community for 30 years," he said.

ESSAY **STEFAN SAVAGE** *Computer science and engineering, University of California, San Diego*

In Planning Digital Defenses, the Biggest Obstacle Is Human Ingenuity

Security is a curious concept, part perception and part prognostication. Webster's captures both sides of this dichotomy in its definition: "freedom from danger; freedom from fear."

Fear concerns a perceived threat; danger reflects what actually threatens us. We fear attacks that never come and live blissfully unaware of true dangers around the corner. This uncertainty is only intensified when our security concerns are transformed by changes in technology.

Indeed, technology and its abuse evolve hand in hand. Just as the internal combustion engine begat highway accidents and auto theft, many of the most visible and transformative successes of computing technology — e-mail, databases, e-commerce, the Web and so on — have ushered in whole new classes of abuse.

But the evolution of computer security is not merely some dark mirror, passively reflecting advances in technology. While technology provides new opportunities for threats, these become true dangers only when there is a motivation to exploit them and a means to do so. Anticipating security threats is not merely a matter of reasoning abstractly about how new technology might raise new risks; it requires an understanding of human nature.

Today, the evolution of computer abuse — and therefore of computer security — is driven by commerce. Botnets, spam, phishing, banking trojans, identity theft and so on are all commercially motivated enterprises perfected in a constant arms race with a well-financed computer security industry.

As little as a decade ago, this ecosystem did not exist. The computer viruses and worms of the 20th century were joy riders, driven primarily by an ambition for notoriety.

But once it became possible to make money from computer infection, whether through advertising (like spam) or theft (like stealing bank account credentials), this economic engine fed a bloom in online crime that we are still experiencing.

Such economically motivated attacks are unlikely to disappear, and we can expect new threats to directly reflect each new technical innovation in how money is used, moved and stored. Emerging cellphone-based payment systems, automated banking transfers and the increasingly liquid markets for online goods in multiplayer games will all be ripe targets for online crooks.

While criminal profit-seeking is perhaps the largest force transforming the computer security landscape today, it is by no means the only one. Another is the large-scale collection and use of personal data.

As we leave ever more detailed online footprints — via purchasing, browsing and social relationships — a vast "big data" ecosystem has emerged to collect, process and resell this information. Concerns about this issue are typically framed in terms of privacy: How much do I want others to know about me? How might it affect my ability to get health insurance, employment or credit?

While these are important questions, they do not capture the full extent of how this data might be used — not just to extract information about people's desires and social relationships, but to use that understanding to affect their behavior. Nor would this be limited to the banal goal of getting you to purchase a particular product; it could be used for Internet-scale social monitoring and manipulation.

The ease with which we adopt online personas and relationships has created a collective blind spot that computer technology is well suited to exploit. Advances in natural-language processing and data mining make it entirely feasible to mint millions of "social bots," each establishing online friendships with their targets like virtual con men, each building trust over time and delivering personalized messages designed to elicit information, sway opinion or call to action.

This idea, which one of my colleagues has called "social architecture," completely upends traditional computer security concerns: The threat is not of humans controlling or monitoring our computers, but precisely the converse.

Finally, there is growing potential for the abuse of computers as an instrument of war. The obvious issues involve espionage and information theft, but the real transformation is much broader.

The Stuxnet worm, designed to sabotage gas centrifuges in Iran, made it clear that computer attacks can have physical, real-world consequences — a particularly troubling precedent because computing capabilities are now embedded in virtually every aspect of our lives. The power we use, the water we drink, the cars, planes and trains we travel in, the elevators and air-conditioning in our buildings, even many of our children's toys — all are controlled by computers.

A parallel trend, fueled by cheap wireless connectivity, is that these devices are increasingly networked. And while few of these systems have been attacked in anger, it is this very fact that leads most of them to be rife with vulnerabilities — a sheltered ecosystem with no immunity to attacks from an outside invader.

Earlier this year, my colleagues and I demonstrated weaknesses that allowed us to remotely infiltrate, track and control popular automobiles more than 1,000 miles away. Other researchers have demonstrated remote attacks on implantable cardiac defibrillators, smart power meters, utility control networks and so on.

The crucial question is whether these are merely Chicken Little fears or real dangers. And the answer will be a matter not of technology but of politics. Do conflicting powers believe that such attacks will advance their aims better than alternatives, that they are worth the effort to develop, that they are worth the risks of retaliation?

There is a tendency to believe that computer security is different from other security. Maybe because computing is mechanistic and predictable, we like to think that security questions should succumb to some form of deterministic analysis.

But security is at its heart a human issue. It is about conflict, and computers are merely a medium by which conflict can be expressed. The future of computer security, then, is less about the future of technology than it is about the future of human relations.

THE WEB TO WATSON

1990 The first Web browser is invented by Tim Berners-Lee.

1995 CompuServe and America Online begin to provide dial-up Internet service.

1995 Microsoft begins selling Windows 95.

2001 Apple introduces the iPod music player.

2004 Mark Zuckerberg launches Thefacebook.

2007 Apple introduces the iPhone.

2007 Amazon releases the Kindle.

2010 Apple releases the iPad.

2011 Watson, an IBM supercomputer, beats the top two "Jeopardy!" players.

THE NEW YORK TIMES

The Future of Computing

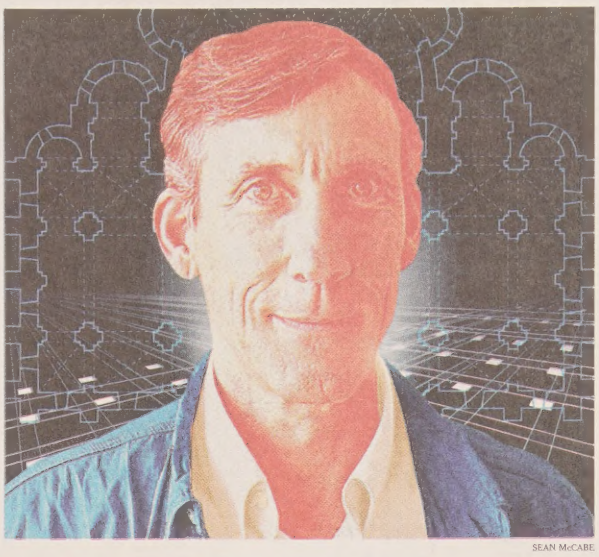
Looking Backward to Put New Technologies in Focus

By CLAUDIA DREIFUS

BELLINGHAM, Wash. — More than most of us, the science historian George Dyson spends his days thinking about technologies, old and very new. His 1986 book "Baidarka" was a meditation on an ancient Aleut kayak.

Eleven years later, in "Darwin Among the Machines," he wrote of the history of artificial intelligence. "Project Orion," in 2002, focused on an abortive NASA project to use nuclear bombs to power space rockets. "Turing's Cathedral," his reconstruction of the early moments of modern digital computing, will be published in March.

Though this 58-year-old author's works are centered on technology, they often have an autobiographical subtext. Freeman Dyson, the physicist and mathematician who was a protagonist of Project Orion, is his father. Esther Dyson, the Internet philosopher and high-tech investor, is his sister. We spoke for three hours at his cottage here, and later by telephone. A condensed and edited version of the conversations follows.



SEAN McCABE

Why did you spend 10 years researching "Turing's Cathedral"?

It's an important story. And a good one! I don't know a single person who is not immersed in the digital universe. Even people who are strongly anti-technology are probably voicing that view on a Web site somewhere. Third-world villagers without electricity have cellphones. So we are all living in this digital world that started from zero.

With many forms, we have no idea how they began. But the digital world actually goes back to a single point — the Institute for Advanced Study in Princeton in the late 1940s and early 1950s. The story I tell in my book is of how at the end of World War II, John von Neumann and his team of mathematicians and engineers began building the very machine that Alan Turing had envisioned in his 1936 paper, "On Computable Numbers." This was a machine that could answer any question asked of it.

Now, there'd been computing machines before von Neumann's. They were extremely slow. The I.A.S. machine was the first to have an absolutely modern form of memory where you could go to any location at any time. On von Neumann's machine, you put in a 10-bit address and you got back a 40-bit string of code.

Once that was possible, numbers ceased being symbols and began doing things. The numbers have been proliferating ever since. Almost all computers we use today — from our iPads to laptops — are essentially copies of this one.

Aside from its speed, why did von Neumann's computer become the prototype for all others?

Von Neumann was tremendously interested in self-reproducing machines, and he set up the conditions where that was likely to happen. Everything his team did was clearly documented and publicized right away. The machine was not patented. The intention was for it to be copied, which it was, in about 10 different places. It's why copies were made of the copies and are still being made of the copies.

The computer was built to aid in the development of the hydrogen bomb. Why was it needed for that?

There's no way to partially test a hydrogen bomb. A computing machine was needed to model the explosion before the actual test was done. Of course, von Neumann had many interests beyond the bomb. Once the machine was up and running, he used it for weather prediction and to model biological and stellar evolution. Von Neumann certainly supported the idea of building an H-bomb — indeed, he advocated preventive nuclear war against Russia — but he also viewed the bomb as a chance to get a computer built.

Did you ever meet von Neumann?

I don't think I did. He died when I was 4. Nonetheless, I grew up with his computer. It was on campus when I was a child, and it fascinated me. In 1958 — for reasons I explain in the book — the computer was completely shut down, never to run again. After that, the computer building seemed a bit like a morgue with a dead body in it. Something interesting was there. But what was it? Writing this book finally got me behind those closed doors.

The I.A.S. sounds like a remarkable place to grow up. Was it?

In many ways, it was. Wherever you grow up, you think of it as normal. I happened to grow up in a place where people were designing a hydrogen bomb and inventing the digital universe.

My sister, Esther, who is older, remembers more of the great scientists who were there. I have memories of Kurt Gödel, who was a friend of our mother's. Some of the physicists were not particularly child-friendly. When they came to the house, we were not part of the conversation. Edward Teller, he liked children. Hans Bethe did, too. Whenever my sister and I went to Fuld Hall, the main building, you could see doors quickly shut. At one point, someone complained about us. Robert Oppenheimer, who was the director, thereafter ruled that no children could come into the building unescorted.

Einstein's secretary, Helen Dukas, was our baby sitter. I remember once being jumpy. "Why don't you read a book?" she said. "There are no books to read," I snapped. And she went to the shelf and pulled down Thor Hyderdahl's "Kon Tiki." This was the first adult book I'd ever been given. It would shape me.

You left the cocoon of Princeton when you were 16. Why?

I was a rebellious adolescent. It was the '60s. Everyone was rebellious. I hated high school. When they wouldn't let me graduate early because I hadn't taken gym, I quit altogether and went off to British Columbia. It was a time when a lot of kids ran away from home. My father didn't stop me. At first, I worked with this guy who'd built his own boat, and we ran around the Northwest delivering things. I loved it. Canada had real wilderness. British Columbia was like Yosemite in the ocean. Being there was so liberating — getting my own food, making my own living. I built myself a boat in the style of the Aleut-Russian kayak, the baidarka. I'd work on tugboats and fishing boats for a while, and then I'd take my baidarka and explore. I did this for about 20 years.

And today you make your living as a historian of science and technology. How does a high school dropout get to do that?

Hey, this is America. You can do what you want! I love this idea that someone who didn't finish high school can write books that get taken seriously. History is one of the only fields where contributions by amateurs are taken seriously, providing you follow the rules and document your sources. In history, it's what you write, not what your credentials are.

If von Neumann were alive today, what would he be doing?

His greatest interest, at the end, was in biology and neurology. I think he would be studying the brain. And of course, he'd now have the tools to do that. These fantastic new technologies like functional M.R.I. are exactly what he envisioned. Here was someone who used his brain so much. He was interested in how it worked.

I also think von Neumann would probably be doing very different kinds of computing from what he did at the institute. As Darwin wasn't a Darwinist, Johnnie von Neumann would not belong to the school named after him. What we call the Von Neumann architecture is just a very crude approximation of the right way to do computation. In the contemporary computer, 99 percent of the parts are idle most of the time. They just sit there waiting for instruction. The machine does only one thing at a time. However, the computers are so powerful and so cheap that it doesn't really matter — although it would, to him. He'd probably be annoyed that this primitive stuff is named after him.

And what about Alan Turing?

Well, he'd be almost 100. And he died at 41. He gave us this one revolution, and we really don't know what the next one might have been because he was just getting started. He died being interested in biology, though we can't guess too much about this because he didn't leave many papers. I'm sure he'd be working on something that would surprise. It would be something that we just cannot imagine.

ESSAY **DAVID PATTERSON** *Computer science, University of California, Berkeley*

Computer Scientists May Have What It Takes to Help Cure Cancer

The war against cancer is increasingly moving into cyberspace. Computer scientists may have the best skills to fight cancer in the next decade — and they should be signing up in droves.

One reason to enlist: Cancer is so pervasive. In his Pulitzer Prize-winning book, "The Emperor of All Maladies," the oncologist Siddhartha Mukherjee writes that cancer is a disease of frightening fractions: One-fourth of deaths in the United States are caused by cancer; one-third of women will face cancer in their lifetimes; and so will half of men.

As he wrote, "The question is not if we will get this immortal disease, but when."

Dr. Mukherjee noted that surprisingly recently, researchers discovered that cancer is a genetic disease, caused primarily by mutations in our DNA. As well as providing the molecular drivers of cancer, changes to the DNA also cause the diversity within a cancer tumor that makes it so hard to eradicate completely.

The hope is that by sequencing the genome of a cancer tumor, doctors will soon be able to prescribe a personalized, targeted therapy to stop a cancer's growth or to cure it.

According to Walter Isaacson's new biography "Steve Jobs," a team of medical researchers sequenced the Apple executive's pancreatic cancer tumor and used that information to decide which drug therapies to use. Since Mr. Jobs's cancer had already spread, this effort was even more challenging. Each sequencing cost $100,000.

Fortunately for the rest of us, the cost of turning pieces of DNA into digital information has improved: The costs dropped a hundredfold in the last three years. The tipping point before widespread use is believed to be $1,000 per individual genome, which is a reason for the major investment in reducing its cost. Given such dramatic improvement, we could soon afford to sequence the genomes of the millions of cancer patients, which only billionaires could afford a few years ago.

How can computer scientists help?

First, as recently reported in this newspaper, the cost of millions of short reads of one cell by a gene sequencing machine is dwarfed by the data processing costs to turn them into a single usable three-billion-base-pair digital representation of a genome. To make personalized medicine affordable for everyone, we need to drive down the information processing costs.

Second, we need to collect cancer genomes in a repository and make them available to scientists and health professionals. The computer scientist David Haussler of the University of California, Santa Cruz, for example, is creating one. Plans are that this five-petabyte (5,000,000,000,000,000 bytes) store will house more than 20,000 genomes.

Third, finding a personalized, targeted therapy for each tumor among myriad possible combinations of drugs is like finding a very small needle in a very large haystack. Researchers are exploring the engagement of people when traditional hardware and software are not up to the task.

An inspirational example is the Foldit game — developed by the computer scientist Zoran Popovic at the University of Washington — that recently attracted thousands of volunteers to uncover the structure of an enzyme important to H.I.V. research.

Cancer tumor genomics is just one example of the Big Data challenge in computer science. Big Data is unstructured, uncurated and inconsistent, and housing it often requires a thousand-fold increase in size over traditional databases. It is not pristine data that can be neatly stored in rows and columns. YouTube alone holds nearly one exabyte of videos, which is one trillion megabytes, or 1,000,000,000,000,000,000 bytes.

The Big Data research challenge is to develop technology that can obtain timely and cost-effective answers to Big Data questions. A Berkeley team of eight faculty members and 40 Ph.D. students is rising to that challenge via three initiatives: inventing algorithms based on statistical machine learning; harnessing many machines in the cloud; and developing crowd-sourcing techniques to get people to help answer questions that prove too hard for our algorithms and machines.

Algorithms, machines and people gave our new lab its name: the AMP Lab.

AMP technology could help the war on cancer. It needs new algorithms to find those needles in haystacks. To process genome data faster and more cheaply, the war needs new infrastructure to use many machines in the cloud simultaneously. And it needs to be able to engage the wisdom of the crowd when the problems of cancer genome discovery and diagnosis are beyond our algorithms and machines.

It may have been true once that expertise in computer science was needed only by computer scientists. But Big Data has shown us that's no longer the case. It is entirely possible that we have the skill sets needed now to fight cancer and to advance sciences in myriad other ways.

The night after we made that argument, I awoke in the middle of the night with this question etched into my mind: Given that millions of people do have and will get cancer, if there is a chance that computer scientists may have the best skill set to fight cancer today, as moral people aren't we obligated to try?

ESSAY **THEODOR HOLM NELSON** *Founder, Project Xanadu*

Full Speed Ahead, Without a Map, Into New Realms of Possibility

More and more people are looking to computers to save the world, but the people who run them certainly don't know how. Nobody's in charge, not even Google, though everyone in the dot-com world pretends. They're all too busy with I.P.O.'s and market share, trying to start fads or come up with idiotic names.

Nobody imagined the vastness of the Internet, not even the kids who built it, or we wouldn't be running out of Web addresses. We are in a world nobody designed or expected, driving full tilt toward — a wall? a cliff? a new dawn? We must choose wisely, as if we could.

On the one hand, we are getting bread and circuses, vast freebies unimaginable scant years ago — free e-mail, phone calls and maps, acres of picture space. On the other hand, somebody or something is reading your mail, and that same somebody or something is looking for new ways to control your future.

Some things are more and more fabulous, some things are more threatening and oppressive, except we don't all agree on which is which. Are Facebook and Google marvelous ways of communicating, or a threat to our privacy? Yes!

In the face of all this, it is absolutely impossible to say what will happen. So let me try.

Theodor Holm Nelson is a well-known dissenter in the computer field. Among other things, he invented the Web browser's "back" button.

DECONSTRUCTING THE INTERFACE The customary computer interface will go away. That is, the standard face of computers — the PARC User Interface, or P.U.I. — will fall apart. First created at Xerox for easy use by secretaries, the P.U.I. became the Macintosh, Windows and then the face of the World Wide Web. Actually it is a fig leaf hiding the structures beneath, in their hierarchical complexity.

In the old days — through the 1970s — all computer users dealt directly with internal hierarchy, typing notes to mechanisms that actually ran the computer. This all changed in the '80s. The first P.U.I. to reach the public was the Macintosh, built by Steve Jobs to look easy — but taking away the right to program and instead creating cattle pens called "applications."

The last two decades have been largely an arms race between Apple's interface (the Macintosh) and Microsoft's (called Windows).

The interface also gave shape to the World Wide Web. In the 1990s, two university students, Eric Bina and Marc Andreessen, put a PARC User Interface around Tim Berners-Lee's page format (HTML). This frame, now called the browser, made the Web take off, giving a puppet theater to programmers with many different obsessions.

Now major players are deconstructing the P.U.I. For instance, Facebook gives you something like a Web site with no need to build one. Instead of the Web's interface frame, Facebook pours out rivers of user-supplied content.

Just as significant, Mr. Jobs — who originally brought the P.U.I. to the public — threw it away when he brought us the iPhone and iPad. There's no more visible hierarchy, and the right to program has come back. Now all of us can create our own cattle pens!

MORE OF THE SAME That is usually the safest prediction about anything. So for tomorrow's computer world, I confidently predict more of the same, but much more so — louder and more intrusive, with more interruptions, more security threats, more monopolies and, of course, worse interfaces.

The Web will get even more chaotic, with new forms of annoyance, temptation and danger. There will be more and more software settings nobody can get right, and the phone support people in India who talk you through the menus will be taught new slang to make your hours with them seem more comfortable.

WILDER SPECULATIONS There will be a secret porn channel for the Department of Homeland Security's body scans.

Facebook will team up with the Library of Congress to bring real-time history streams to the user. Be a friend of Benjamin Franklin! But it will somehow lack suspense.

A new copyright law will forbid the typing of any sentence that is not in the public domain. The National Security Agency will be told to enforce this, but without additional financing.

Other new laws will forbid posting anything that is of possible use to terrorists, including music, history and recipes. Some will think the paper publishing industry is behind this.

UNIFIED DOCUMENTS, VISIBLE CONNECTIONS But seriously, the one bright hope I see is the generalization of documents. Since 1974, computer documents have imitated paper, with no inkling of the powers interactive documents might provide — in particular, allowing documents to be connected side by side.

So far there's been no way to connect documents in detail. We may expect this at last to be fixed, allowing different document formats to be visibly linked, with visible connections among side-by-side documents. Stripes and arrows across the screen — among words, sentences and paragraphs — will at last help us clarify the structure of thought.

That's my glass, darkly. Is the glass half empty or half full? Or perhaps even both?

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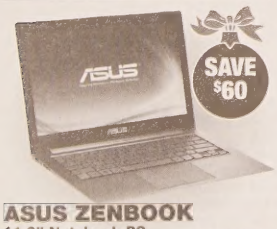

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